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VERTICAL DISTRIBUTION AND PERSISTENCE OF HEAVY METALS IN SOILS FROM INACTIVE MINING DUMPS IN THE JIU VALLEY, ROMANIA

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Abstract: *Mining waste dumps represent important long-term sources of environmental contamination in former coal mining regions. The Jiu Valley, one of Romania's most important historical coal mining areas, contains numerous inactive mining dumps that continue to influence soil quality after mine closure. The present study evaluates the vertical distribution and persistence of heavy metals in soils collected from fourteen inactive mining dumps located within the former mining perimeters of Uricani, Lupeni, Vulcan, Livezeni and Petrila. Concentrations of chromium (Cr), copper (Cu) and nickel (Ni) were compared for all investigated dumps, while zinc (Zn), cobalt (Co) and lead (Pb) were included where available in the dataset. The results showed that Cr concentrations ranged between 33.48 and 38.43 mg/kg in the surface layer and between 31.47 and 36.12 mg/kg in the deeper layer. Copper concentrations varied between 54.19–58.92 mg/kg and 47.42–51.55 mg/kg, respectively, while Ni reached maximum values of 87.44 mg/kg in the 0–20 cm layer and 83.07 mg/kg in the 20–40 cm layer. A general decrease in concentration with depth was observed, but the reduction was relatively moderate. The calculated decreases ranged between 3.2–8.7% for Cr, 8.6–17.1% for Cu, 2.9–7.9% for Ni, 15.5–20.6% for Zn, 8.2–12.4% for Co and 19.4–25.3% for Pb. The limited decrease between the two investigated layers indicates that contamination is not restricted to the surface horizon but persists within the waste material. The results support long-term environmental monitoring and rehabilitation strategies for inactive mining dumps in the Jiu Valley.*

Keywords: *heavy metals; inactive mining dumps; soil contamination; vertical distribution; environmental monitoring; Jiu Valley*

1. Introduction

Mining activities have played a fundamental role in the economic development of many industrial regions worldwide. However, the extraction and processing of mineral resources generate large quantities of waste materials that may continue to affect environmental quality long after mining operations cease. Among the most visible legacies of historical mining activities are waste dumps and tailings deposits, which frequently remain within the landscape as potential sources of soil, water and air contamination [1, 2].

Heavy metals represent one of the main environmental concerns associated with mining waste deposits. Unlike many organic pollutants, heavy metals are not biodegradable and may persist within environmental compartments for long periods. Their accumulation in soils can alter soil functions, affect vegetation development and contribute to ecological degradation. Furthermore, heavy metals may become mobilized through weathering processes and subsequently enter surrounding ecosystems through runoff, wind erosion or groundwater infiltration [3, 4, 5].

The environmental behaviour of heavy metals in contaminated soils is strongly influenced by their vertical distribution. The assessment of contaminant concentrations at different depths provides valuable information regarding pollutant persistence, mobility and potential environmental risks. In natural soils, metal concentrations frequently decrease with depth because atmospheric deposition and biological activity are concentrated near the surface. In contrast, soils developed on mining waste deposits may exhibit different vertical patterns because contaminants are incorporated directly into the waste material during disposal operations [6, 7, 8, 9].

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Understanding the vertical distribution of heavy metals is particularly important for the design of monitoring programmes and rehabilitation measures. If contamination is limited primarily to the surface horizon, stabilization and revegetation measures may significantly reduce environmental risks. Conversely, when elevated concentrations persist at greater depths, rehabilitation strategies must consider the entire waste mass as a long-term contamination source. Consequently, the evaluation of contaminant persistence throughout the soil profile represents an essential component of post-mining land management [10, 11, 12].

The Jiu Valley represents the most important historical hard coal mining basin in Romania. More than one century of mining activity generated numerous waste dumps associated with coal extraction and processing operations. Although the gradual closure of mines has reduced direct industrial emissions, many inactive dumps remain present throughout the region. Previous investigations conducted in the Jiu Valley identified elevated concentrations of heavy metals in soils developed on mining waste deposits and highlighted the existence of contamination hotspots associated with several inactive dumps [13, 14, 15, 16, 17]. However, most available studies focused primarily on surface contamination, while information regarding contaminant persistence at greater depths remains limited.

The present study addresses this issue by investigating the vertical distribution of heavy metals in soils collected from fourteen inactive mining dumps distributed throughout the Jiu Valley. The selected dumps represent the principal inactive mining waste deposits remaining after the restructuring of the regional coal industry and provide a representative overview of post-mining environmental conditions.

Therefore, the aim of this study was to assess the persistence of heavy metal contamination within inactive mining dumps by comparing concentrations in the surface (0–20 cm) and subsurface (20–40 cm) soil layers. Particular attention was given to chromium (Cr), copper (Cu), nickel (Ni), zinc (Zn), cobalt (Co) and lead (Pb), elements frequently associated with mining-related contamination. The obtained results contribute to a better understanding of contaminant behaviour within mining waste deposits and provide useful information for environmental monitoring and rehabilitation planning in the Jiu Valley.

2. Materials and Methods

Study Area

The study was conducted in the Jiu Valley, located in the south-western part of Romania, within Hunedoara County. The region represents the country's most important historical hard coal mining basin and has been subjected to intensive mining activities for more than one century. The exploitation of coal resources generated large quantities of waste rock and processing residues, which were deposited in numerous mining dumps distributed throughout the valley.

Following the gradual closure and restructuring of mining operations, many of these deposits remained within the landscape and continue to represent potential sources of environmental contamination. The investigated sites are associated with the former mining perimeters of Uricani, Lupeni, Vulcan, Livezeni and Petrila and constitute some of the most representative inactive mining dumps currently present in the Jiu Valley. The geographical distribution of the fourteen investigated dumps is presented in Figure 1.

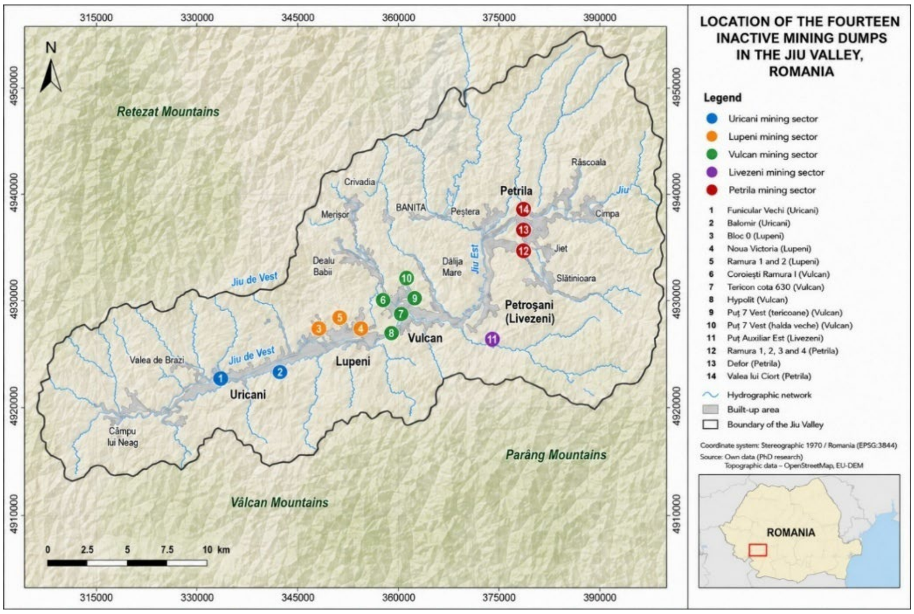

Fig. 1. Location of the fourteen inactive mining dumps investigated in the Jiu Valley, Romania

As illustrated in Figure 1, the investigated dumps are distributed along the entire east-west axis of the Jiu Valley. The western sector includes the Uricani dumps (Funicular Vechi and Balomir), followed by the Lupeni sector (Bloc 0, Noua Victoria and Ramura 1 and 2). The central part of the basin is represented by the Vulcan mining sector, while the eastern sector includes the Livezeni and Petrila dumps. This distribution provides a representative overview of the principal inactive mining waste deposits remaining after mine closure.

The climate of the region is characterized by moderate continental influences, with annual precipitation generally ranging between 700 and 1000 mm and mean annual temperatures between 7 and 9°C. These climatic conditions favour weathering processes, erosion and runoff generation, all of which may contribute to the redistribution of contaminants from mining waste deposits into surrounding environmental compartments.

Soil Sampling and Analytical Procedures

The assessment of heavy metal persistence was based on the investigation of two soil layers commonly used in contaminated land studies. The upper layer (0–20 cm) was selected because it is directly influenced by atmospheric deposition, vegetation development and surface runoff processes. The deeper layer (20–40 cm) was investigated in order to evaluate contaminant persistence within the waste material and to identify possible vertical migration trends.

A conceptual representation of the adopted sampling strategy is presented in Figure 2.

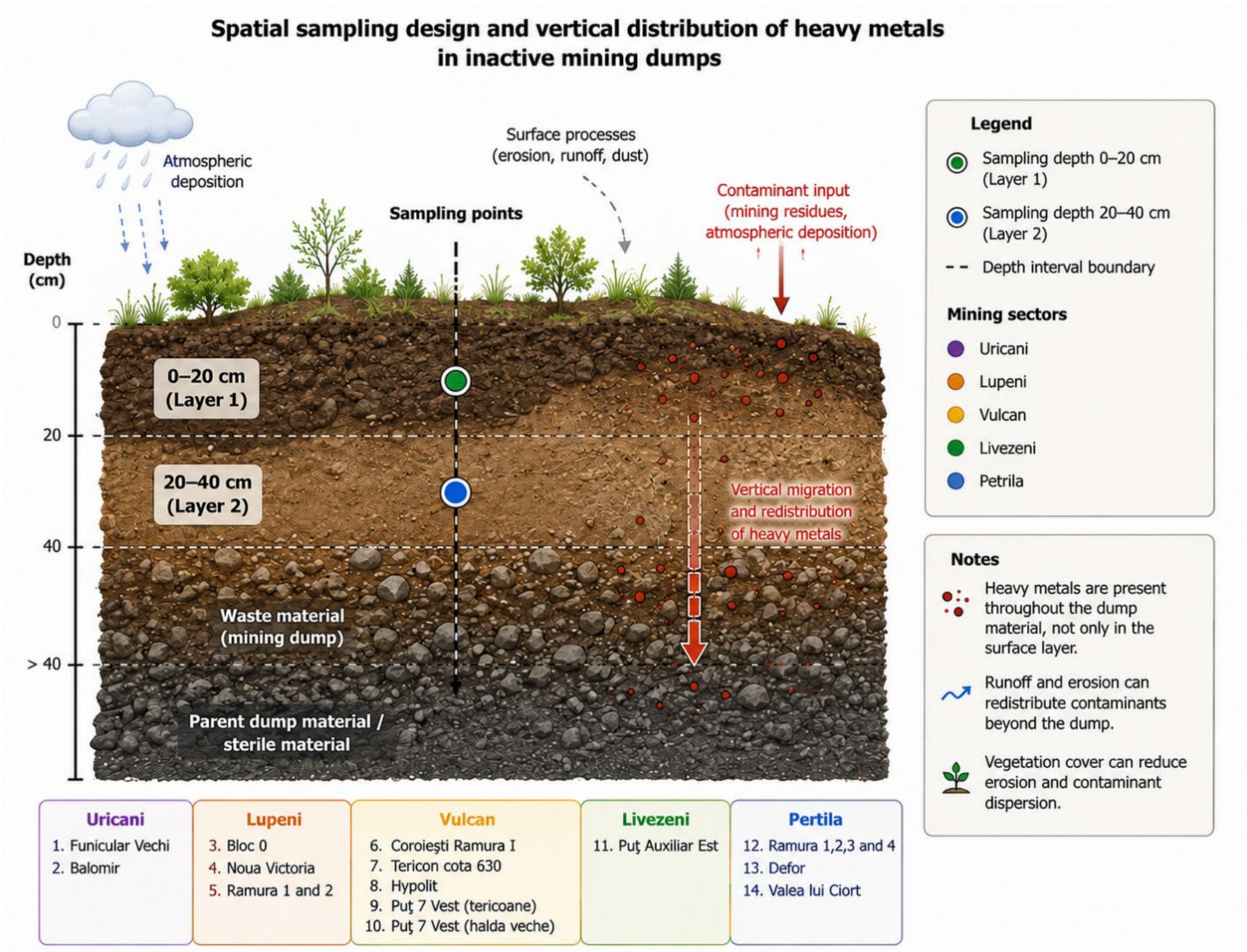

Fig. 2. Conceptual representation of the vertical soil sampling strategy and heavy metal distribution within inactive mining dumps

The selected depth intervals allowed the comparison between surface and subsurface contamination conditions and provided information regarding the distribution of contaminants within the dump profile. The investigated metals included chromium (Cr), copper (Cu), nickel (Ni), zinc (Zn), cobalt (Co) and lead (Pb), elements commonly associated with mining-related environmental contamination.

These metals were selected because of their persistence, potential toxicity and frequent occurrence within mining waste deposits. Previous investigations conducted in the Jiu Valley identified these elements as the principal contaminants associated with inactive mining dumps, making them suitable indicators for evaluating long-term contamination patterns [13, 14, 15, 16, 17].

Data Processing and Interpretation

The concentrations determined for the two investigated soil layers were compared in order to evaluate the vertical distribution of contaminants and identify differences in contaminant persistence among the investigated dumps.

For each metal, the percentage decrease between the 0–20 cm and 20–40 cm layers was calculated using Equation (1):

$$\mathrm{Reduction}(\%) = \frac{C_{0-20} - C_{20-40}}{C_{0-20}} \times 100 \quad (1)$$

where C_{0-20} represents the concentration determined in the surface layer, and C_{20-40} represents the concentration determined in the deeper layer.

The calculated reductions were subsequently used to assess the degree of contaminant persistence and to identify metals exhibiting higher or lower mobility within the investigated profile.

The interpretation of the obtained concentrations was performed using the normal values established by Romanian environmental legislation, respectively Order No. 756/1997 for the assessment of environmental pollution [18]. The reference values considered during interpretation were 30 mg/kg for Cr, 20 mg/kg for Cu, 20 mg/kg for Ni, 100 mg/kg for Zn, 15 mg/kg for Co and 20 mg/kg for Pb.

In addition to the comparison between soil layers, the results were analysed comparatively among mining sectors in order to identify spatial differences in contamination intensity and persistence. The obtained data were synthesized using tables and graphical representations to facilitate the identification of contamination patterns and support the discussion of environmental implications.

3. Results and Discussion

Heavy Metal Concentrations in the Surface Soil Layer (0–20 cm)

The concentrations of heavy metals determined in the surface soil layer (0–20 cm) of the investigated inactive mining dumps are presented in Table 1. This soil horizon is particularly important from an environmental perspective because it is directly exposed to atmospheric deposition, erosion processes, vegetation development and potential human contact. Consequently, the contamination status of the surface layer is commonly used as a first indicator of environmental degradation associated with mining waste deposits.

Table 1. Mean concentrations of heavy metals in the 0–20 cm soil layer from inactive mining dumps in the Jiu Valley (mg/kg)

No.	Inactive mining dump	Cr	Cu	Ni	Zn	Co	Pb
1	Funicular Vechi	36.40	58.92	85.70	-	-	-
2	Balomir	34.62	58.03	84.72	-	-	-
3	Bloc 0	35.62	57.23	86.28	-	-	-
4	Noua Victoria	34.03	56.73	82.26	-	-	-
5	Ramura 1 and 2	35.90	58.62	83.23	-	-	-
6	Coroiești Ramura I	33.49	55.73	76.70	-	-	-
7	Tericon cota 630	36.55	56.26	78.28	-	-	-
8	Hypolit	37.42	55.08	74.02	-	-	-
9	Puț 7 Vest (tericoane)	37.79	57.05	78.58	-	-	-
10	Puț 7 Vest (halda veche)	38.43	57.48	81.19	-	-	-
11	Puț Auxiliar Est	34.15	54.19	72.28	123.50	22.08	-
12	Ramura 1, 2, 3 and 4	38.37	55.17	87.44	124.54	23.67	19.80
13	Defor	37.34	58.32	86.96	126.03	22.55	19.62
14	Valea lui Ciort	33.48	56.61	82.38	121.73	21.95	19.37

Note: "-" indicates parameters not included in the available dataset for the respective dump.

The obtained results indicate the widespread presence of heavy metals throughout all investigated mining dumps. Chromium concentrations ranged between 33.48 mg/kg and 38.43 mg/kg, exceeding the normal value of 30 mg/kg established by Romanian environmental legislation in all analysed sites. Although the exceedances were relatively moderate, the results confirm the persistent influence of mining waste materials on soil quality across the entire Jiu Valley mining region.

Copper concentrations showed a narrower variability, ranging from 54.19 mg/kg at Puț Auxiliar Est to 58.92 mg/kg at Funicular Vechi. All measured values exceeded the normal concentration of 20 mg/kg by more than

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two times, indicating a substantial enrichment of surface soils in comparison with uncontaminated conditions. Similar enrichment patterns have been reported for mining waste deposits developed on coal-bearing formations, where copper may be associated with sulphide minerals and waste rock materials [3, 6, 12].

Nickel represented the dominant contaminant among the analysed elements. Concentrations varied between 72.28 mg/kg and 87.44 mg/kg, corresponding to values approximately three to four times higher than the normal concentration established by national legislation. The highest nickel concentration was recorded at the Ramura 1, 2, 3 and 4 dump, followed closely by Defor and Bloc 0. Such values indicate the long-term persistence of nickel within the waste material and confirm its importance as a key contamination indicator in the Jiu Valley mining area.

To facilitate the comparison among sites, the concentrations of Cr, Cu and Ni are illustrated in Figure 3.

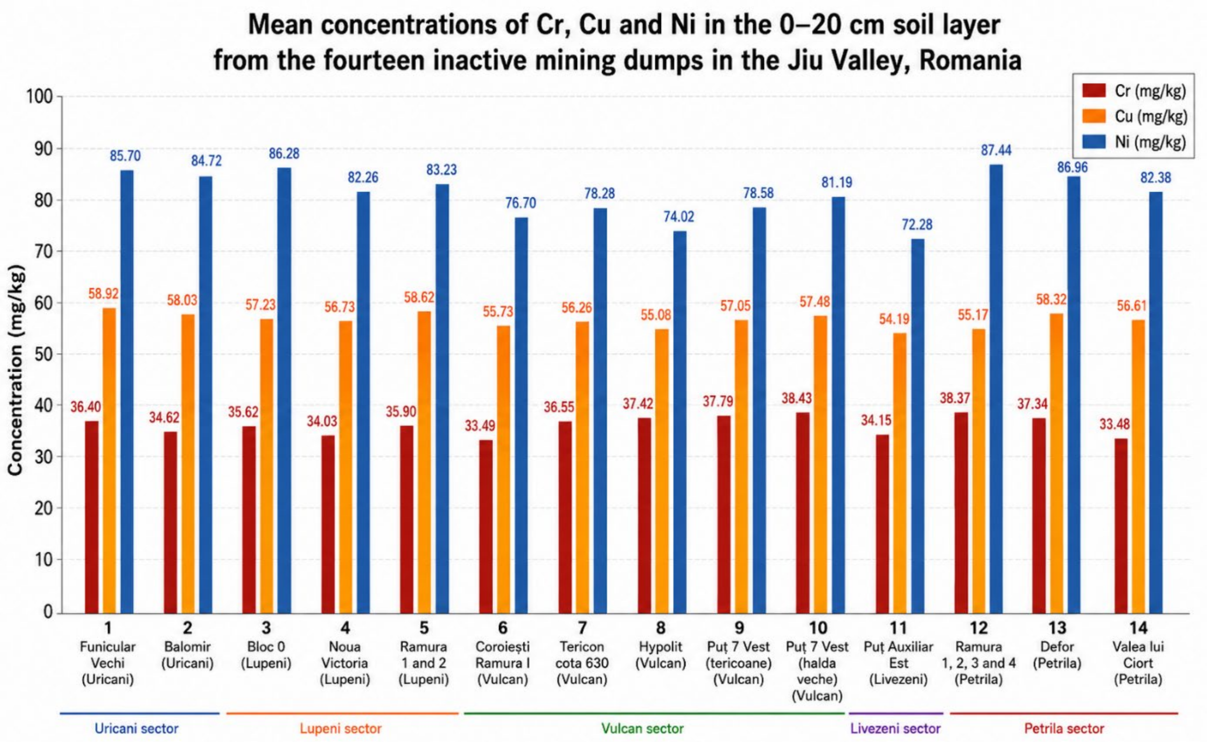

Fig. 3. Mean concentrations of Cr, Cu and Ni in the 0–20 cm soil layer from inactive mining dumps

The graphical representation highlights two important aspects. First, chromium concentrations exhibit relatively limited variability among the investigated dumps, suggesting a broadly similar lithological origin of the deposited waste material. Second, nickel concentrations consistently exceed both chromium and copper concentrations in all investigated locations, demonstrating the dominant contribution of nickel to the overall contamination profile of the mining dumps.

The highest contamination levels were generally associated with the Petrila mining sector. The Ramura 1, 2, 3 and 4 and Defor dumps exhibited elevated concentrations for nearly all investigated elements, including Zn, Co and Pb. Zinc concentrations exceeded 120 mg/kg at both sites, while cobalt concentrations ranged between 22.55 and 23.67 mg/kg. Lead concentrations remained slightly below the normal value of 20 mg/kg, but their presence close to this reference level indicates the influence of mining-derived materials on soil quality.

A comparison among mining sectors reveals a gradual increase in contamination intensity from west to east. The Uricani and Lupeni sectors generally displayed moderate contamination levels, whereas the Petrila sector contained the highest concentrations for most analysed elements. This pattern is consistent with the larger dimensions and longer operational history of several Petrila mining dumps, which accumulated substantial quantities of waste material during decades of mining activity.

Overall, the results demonstrate that the surface soils developed on inactive mining dumps remain significantly influenced by historical mining activities. The persistent exceedance of normal values, particularly for nickel and copper, confirms that these deposits continue to represent potential sources of environmental contamination despite the cessation of mining operations. The observed contamination patterns provide a baseline for evaluating contaminant persistence at greater depths and for assessing the effectiveness of future rehabilitation measures.

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Heavy Metal Persistence in the Subsurface Soil Layer (20–40 cm)

The concentrations of heavy metals determined in the 20–40 cm soil layer are presented in Table 2. This layer was analysed in order to evaluate whether contamination is restricted mainly to the surface horizon or persists within the deeper part of the waste material. Such information is important because inactive mining dumps are not natural soil profiles, but anthropogenic deposits composed of heterogeneous waste materials accumulated during mining operations.

Table 2. Mean concentrations of heavy metals in the 20–40 cm soil layer from inactive mining dumps in the Jiu Valley (mg/kg)

No.	Inactive mining dump	Cr	Cu	Ni	Zn	Co	Pb
1	Funicular Vechi	34.22	51.55	81.41	-	-	-
2	Balomir	32.54	50.78	80.48	-	-	-
3	Bloc 0	33.48	50.08	81.97	-	-	-
4	Noua Victoria	31.99	49.64	78.15	-	-	-
5	Ramura 1 and 2	33.75	51.29	79.07	-	-	-
6	Coroiești Ramura I	31.48	48.76	72.86	-	-	-
7	Tericon cota 630	34.36	49.23	74.37	-	-	-
8	Hypolit	35.17	48.20	70.32	-	-	-
9	Puț 7 Vest (tericoane)	35.52	49.92	74.65	-	-	-
10	Puț 7 Vest (halda veche)	36.12	50.29	77.13	-	-	-
11	Puț Auxiliar Est	32.10	47.42	68.67	103.12	20.09	-
12	Ramura 1, 2, 3 and 4	36.07	48.27	83.07	103.99	21.54	15.84
13	Defor	35.10	51.03	82.61	105.24	20.52	15.70
14	Valea lui Ciort	31.47	49.53	78.26	101.64	19.97	15.50

Note: "-" indicates parameters not included in the available dataset for the respective dump.

The results show that heavy metals remain present in the 20–40 cm layer at concentrations that are still environmentally relevant. Chromium concentrations ranged from 31.47 mg/kg at Valea lui Ciort to 36.12 mg/kg at Puț 7 Vest (halda veche). Although these values are lower than those determined in the surface layer, they still exceed the normal value of 30 mg/kg in all investigated dumps. This indicates that chromium is not only accumulated at the surface but is also incorporated within the waste material.

Copper concentrations in the 20–40 cm layer ranged between 47.42 mg/kg at Puț Auxiliar Est and 51.55 mg/kg at Funicular Vechi. These values remain considerably higher than the normal value of 20 mg/kg, confirming the persistence of copper contamination at depth. The relatively narrow range of concentrations suggests that Cu is distributed throughout the waste material in a relatively consistent manner, although surface enrichment remains more evident than for chromium and nickel.

Nickel continued to show the highest concentrations among the analysed elements. Values ranged from 68.67 mg/kg at Puț Auxiliar Est to 83.07 mg/kg at Ramura 1, 2, 3 and 4. Even in the deeper layer, nickel concentrations remained more than three times higher than the normal value established by Romanian legislation. This confirms that nickel represents the most persistent contaminant in the investigated mining dumps and should be considered a priority element in future monitoring programmes.

The persistence of Cr, Cu and Ni in the 20–40 cm layer suggests that contamination is controlled primarily by the composition of the mining waste material rather than only by recent surface processes. In mining dumps, sterile material is deposited in successive layers and frequently contains fragments of coal-bearing rocks, shale, sandstone and associated mineral phases. Consequently, heavy metals may occur throughout the dump profile, producing a relatively continuous contamination source.

Zinc, cobalt and lead were determined mainly in the Livezeni and Petrila sectors. Zinc concentrations remained above 100 mg/kg in the deeper layer, with the highest value recorded at Defor. Cobalt concentrations ranged between 19.97 mg/kg and 21.54 mg/kg, while lead values ranged between 15.50 mg/kg and 15.84 mg/kg in the sites where this element was assessed. In the 20–40 cm layer, lead concentrations remained below the normal value but confirmed its persistence in the subsurface layer.

The highest concentrations in the 20–40 cm layer were generally recorded in the Petrila mining sector, especially at Ramura 1, 2, 3 and 4 and Defor. These sites also showed elevated concentrations in the surface layer, indicating that contamination is vertically persistent and not confined to the upper horizon. This behaviour is particularly relevant for rehabilitation planning, because surface stabilization alone may reduce erosion and dust dispersion but does not remove the contamination source stored in the deeper waste mass.

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Overall, the subsurface results confirm that inactive mining dumps in the Jiu Valley continue to act as long-term reservoirs of heavy metals. The persistence of contamination in the 20–40 cm layer demonstrates the need for monitoring strategies that include both surface and subsurface sampling, especially in areas where future ecological rehabilitation or land reuse is planned.

Vertical Distribution of Heavy Metals and Concentration Decrease with Depth

The comparison between the two investigated soil layers provides valuable information regarding the persistence of heavy metal contamination within inactive mining dumps. To quantify the differences between the surface and subsurface horizons, the percentage decrease in concentration between the 0–20 cm and 20–40 cm layers was calculated for each investigated metal. The obtained values are presented in Table 3.

Table 3. Percentage decrease of heavy metal concentrations between the 0–20 cm and 20–40 cm soil layers

Inactive mining dump	Cr (%)	Cu (%)	Ni (%)	Zn (%)	Co (%)	Pb (%)
Funicular Vechi	4.5	10.2	3.8	-	-	-
Balomir	5.3	12.7	4.6	-	-	-
Bloc 0	6.1	11.4	5.2	-	-	-
Noua Victoria	7.8	13.5	6.0	-	-	-
Ramura 1 and 2	4.9	9.8	4.1	-	-	-
Coroiești Ramura I	8.2	15.4	7.5	-	-	-
Tericon cota 630	5.7	11.9	4.8	-	-	-
Hypolit	3.2	8.6	2.9	-	-	-
Puț 7 Vest (tericoane)	6.9	13.8	5.4	-	-	-
Puț 7 Vest (halda veche)	5.4	12.1	4.7	-	-	-
Puț Auxiliar Est	7.1	14.2	6.8	15.5	8.2	-
Ramura 1, 2, 3 and 4	4.8	10.5	3.9	18.4	9.5	22.1
Defor	6.4	13.7	5.7	16.8	10.3	19.4
Valea lui Ciort	8.7	17.1	7.9	20.6	12.4	25.3

Note: “-” indicates parameters not included in the available dataset for the respective dump.

The calculated reductions reveal important differences in the behaviour of the analysed elements. In general, all investigated metals showed lower concentrations in the 20–40 cm layer, confirming the existence of a vertical contamination gradient. However, the magnitude of the decrease varied considerably among elements, indicating different degrees of persistence within the waste material.

Chromium exhibited the smallest reductions, ranging between 3.2% and 8.7%. The lowest decrease was recorded at Hypolit (3.2%), while the highest reduction was observed at Valea lui Ciort (8.7%). Such limited variation suggests that chromium is relatively uniformly distributed throughout the dump profile. This behaviour is consistent with the geochemical characteristics of chromium-bearing minerals, which are often associated with the parent material composing the waste deposits. Consequently, chromium appears to be strongly controlled by the composition of the deposited sterile material rather than by recent surface accumulation processes.

A similar pattern was observed for nickel. Percentage decreases ranged from 2.9% to 7.9%, representing the lowest overall variability among the investigated metals. The persistence of nickel throughout the soil profile confirms the observations presented in Sections 3.1 and 3.2 and further supports the interpretation that Ni is one of the most stable and persistent contaminants within the inactive mining dumps of the Jiu Valley. From an environmental perspective, this behaviour is particularly important because nickel concentrations exceeded normal values in both investigated layers and across all analysed sites.

Copper displayed intermediate reductions, varying between 8.6% and 17.1%. The highest decreases were recorded at Valea lui Ciort, Coroiești Ramura I and Puț Auxiliar Est. Compared with chromium and nickel, copper appears to be more strongly influenced by surface processes such as weathering, oxidation and leaching. Nevertheless, the relatively high concentrations remaining in the deeper layer demonstrate that copper contamination also extends throughout the waste material.

For zinc and cobalt, the observed decreases ranged between 15.5–20.6% and 8.2–12.4%, respectively. These values indicate a moderate vertical gradient and suggest that part of the contamination is concentrated within the upper soil horizon. However, the persistence of significant concentrations at depth confirms that these elements remain associated with the waste material and are not restricted exclusively to the surface environment.

Lead exhibited the highest reductions among all analysed elements. The calculated decreases ranged from 19.4% at Defor to 25.3% at Valea lui Ciort. This behaviour differs from that observed for chromium and nickel

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and suggests a greater tendency for lead accumulation within the upper soil layer. The higher reductions may be associated with the strong affinity of Pb for organic matter and fine particles, which tend to accumulate near the surface. Although lead concentrations were generally lower than those of the other investigated metals, its vertical behaviour indicates a greater influence of surface-related processes.

The overall vertical distribution pattern is illustrated in Figure 4.

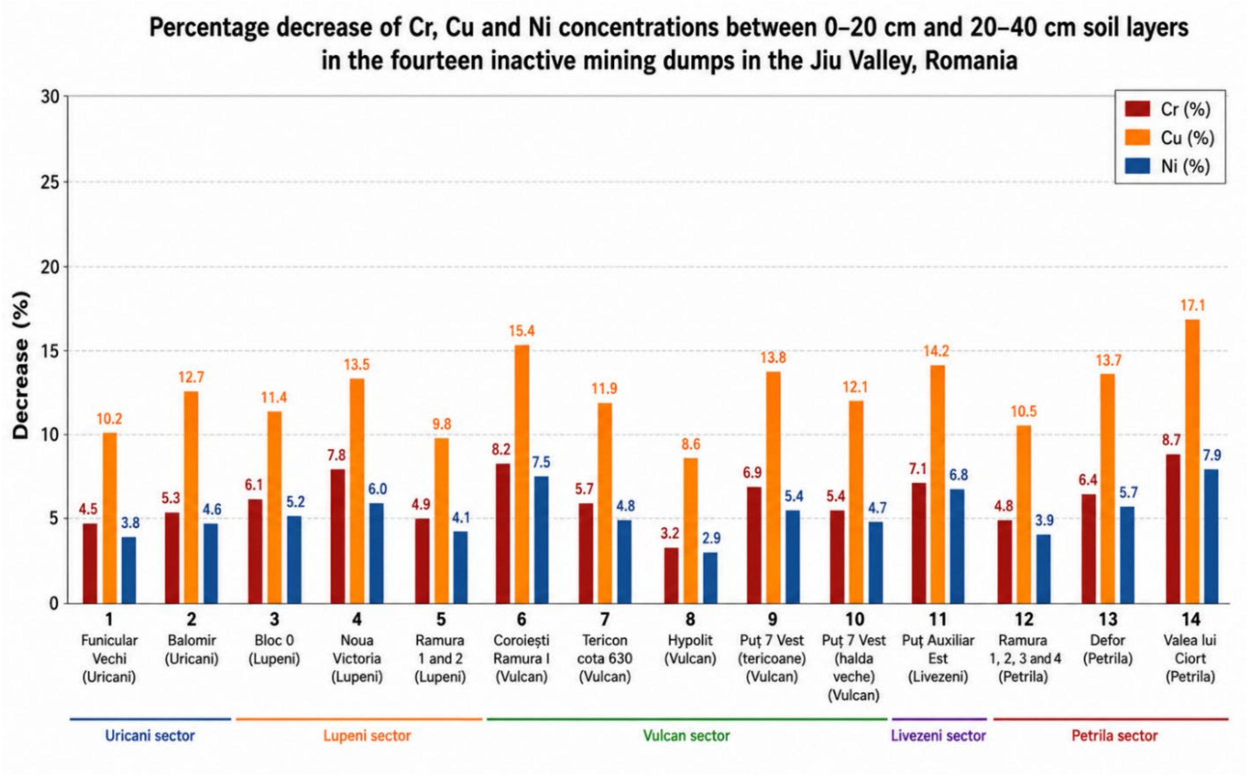

Fig. 4. Percentage decrease of heavy metal concentrations between the 0–20 cm and 20–40 cm soil layers

Figure 4 clearly demonstrates that chromium and nickel exhibit the highest persistence within the waste profile, while lead shows the strongest concentration decrease with depth. Copper occupies an intermediate position, whereas zinc and cobalt display moderate reductions. The consistency of these patterns across multiple mining dumps suggests that the observed behaviour reflects the intrinsic characteristics of the contaminants and the mining waste material rather than isolated site-specific anomalies.

From a rehabilitation perspective, the relatively small differences between the two investigated layers represent one of the most important findings of the study. In natural soils, heavy metal concentrations frequently decrease substantially with depth; however, the reductions observed in the investigated mining dumps remain relatively limited. This indicates that contamination is not restricted to the surface horizon but extends throughout the waste material. As a consequence, environmental assessments based solely on surface samples may underestimate the total contamination burden present within inactive mining dumps.

The results also provide useful information for the design of future monitoring programmes. Since several contaminants remain present at elevated concentrations in the 20–40 cm layer, periodic subsurface investigations should complement routine surface monitoring. Such an approach would improve the understanding of contaminant persistence, support more accurate risk assessments and contribute to the development of more effective rehabilitation strategies for post-mining landscapes in the Jiu Valley.

Comparative Assessment of Mining Sectors and Environmental Implications

The comparative analysis of the investigated mining sectors revealed notable differences in contamination intensity and contaminant persistence. Although elevated concentrations of heavy metals were identified throughout the Jiu Valley, the magnitude of contamination varied among mining perimeters, reflecting differences in geological conditions, mining technologies, waste composition and post-closure evolution.

The Uricani sector, represented by the Funicular Vechi and Balomir dumps, exhibited moderate contamination levels for chromium and nickel but relatively elevated copper concentrations. These results suggest that the waste material deposited in this sector contains a relatively homogeneous geochemical composition and has undergone comparable weathering processes since mine closure.

The limited differences observed between the two investigated dumps indicate a relatively uniform contamination pattern within the western part of the Jiu Valley.

The Lupeni sector, represented by Bloc 0, Noua Victoria and Ramura 1 and 2, displayed contamination levels similar to those observed at Uricani, although slightly higher concentrations of chromium and nickel were recorded at several locations. The moderate variability among the investigated sites may be explained by differences in dump dimensions, age and waste composition. Nevertheless, the overall contamination pattern remained relatively consistent, suggesting that the environmental behaviour of the deposited material is comparable throughout the sector.

Greater variability was observed in the Vulcan mining sector. Coroiești Ramura I, Tericon cota 630, Hypolit and the two Puț 7 Vest dumps exhibited noticeable differences in heavy metal concentrations despite their geographical proximity. Such variability may reflect differences in the lithological composition of the deposited waste material and the historical evolution of individual dumps. In particular, the elevated chromium and nickel concentrations identified at Puț 7 Vest indicate the persistence of contamination sources associated with specific waste deposition practices.

The highest contamination levels were consistently recorded within the Petrila mining sector. The Ramura 1, 2, 3 and 4 and Defor dumps exhibited elevated concentrations for nearly all investigated metals in both analysed soil layers. These sites also recorded some of the highest values for zinc and cobalt and maintained elevated concentrations at depth. The results indicate that the Petrila dumps contain the largest contaminant inventories among the investigated sites and therefore represent the most environmentally significant inactive mining deposits in the Jiu Valley.

The observed spatial pattern suggests a gradual increase in contamination intensity from the western mining sectors towards the eastern part of the basin. Although the exact causes require further investigation, several factors may contribute to this trend, including differences in waste volume, operational duration, geological characteristics of the exploited coal seams and historical waste management practices. Larger dumps generally contain greater quantities of waste material and may therefore act as more significant long-term contamination sources.

From an environmental management perspective, the identified differences among mining sectors are highly relevant. The results demonstrate that rehabilitation priorities should not be established solely on the basis of dump size or visual appearance. Instead, contamination intensity and contaminant persistence should be considered alongside morphometric characteristics, vegetation cover and receptor vulnerability. Dumps exhibiting elevated concentrations in both the surface and subsurface layers should receive particular attention because they represent long-term contamination reservoirs capable of influencing surrounding environmental compartments.

The persistence of heavy metals throughout the investigated profiles also has important implications for ecological rehabilitation programmes. Surface stabilization, phytostabilization and revegetation measures can substantially reduce erosion and dust generation; however, they do not eliminate contaminants stored within the waste mass [11, 19]. Consequently, rehabilitation strategies should be accompanied by long-term environmental monitoring programmes capable of detecting changes in contaminant mobility and ecological condition, since remediation of metal-contaminated soils requires the selection of site-specific technologies adapted to contaminant type, mobility and environmental conditions [20].

The findings of the present study support the development of risk-based post-mining management approaches in the Jiu Valley. By identifying sites characterized by elevated contamination levels and high contaminant persistence, environmental authorities and land managers can allocate resources more efficiently and prioritize interventions where they are most needed. Such an approach would contribute to the sustainable rehabilitation of former mining areas and support the long-term ecological recovery of the region.

Overall, the comparative assessment confirms that inactive mining dumps remain important sources of environmental contamination within the Jiu Valley. Although contamination intensity varies among sectors, the persistence of heavy metals at depth demonstrates that these deposits continue to represent a long-term environmental challenge requiring continuous monitoring and appropriate rehabilitation measures.

4. Conclusions

The present study investigated the vertical distribution of heavy metals in soils collected from fourteen inactive mining dumps located within the Jiu Valley mining basin, Romania. By comparing concentrations measured in the 0–20 cm and 20–40 cm soil layers, the study provided new information regarding contaminant persistence within mining waste deposits and contributed to a better understanding of the long-term environmental legacy of historical coal mining activities in the region.

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The results demonstrated that elevated concentrations of chromium, copper and nickel remain present throughout all investigated dumps, confirming the widespread influence of mining waste materials on soil quality. Among the analysed elements, nickel exhibited the highest concentrations in both investigated layers, while chromium showed the lowest variability among sites. The persistence of elevated concentrations at depths of 20–40 cm indicates that contamination is not restricted to the surface horizon but extends throughout the waste material, reflecting the anthropogenic origin of the investigated deposits.

The comparison between the two soil layers revealed a general decrease in heavy metal concentrations with depth; however, the magnitude of this reduction was relatively limited. Chromium and nickel exhibited the highest persistence, with reductions generally below 10%, whereas lead showed the greatest decrease between the investigated layers. These results suggest that Cr and Ni are strongly associated with the mineral matrix of the deposited waste material, while Pb appears to be more influenced by surface accumulation processes. The observed vertical patterns confirm that inactive mining dumps represent long-term contaminant reservoirs capable of maintaining elevated concentrations even below the surface horizon.

The comparative assessment of mining sectors highlighted significant spatial differences in contamination intensity. The Petrila mining sector, particularly the Ramura 1, 2, 3 and 4 and Defor dumps, consistently recorded the highest concentrations for most investigated elements and exhibited elevated contaminant persistence at depth. In contrast, the Uricani and Lupeni sectors generally showed lower contamination levels, although concentrations remained above normal values for several metals. These differences emphasize the importance of site-specific environmental assessments and demonstrate that rehabilitation priorities should be established based on contamination intensity and persistence rather than solely on dump size or visual characteristics.

From an environmental management perspective, the results indicate that rehabilitation measures focused exclusively on the surface layer may be insufficient to address the total contamination burden stored within inactive mining dumps. Long-term monitoring programmes should therefore include both surface and subsurface investigations in order to accurately evaluate contaminant persistence and identify potential changes in mobility over time. Furthermore, the integration of contamination data with morphometric characteristics, ecological indicators and receptor vulnerability could support the development of more effective risk-based rehabilitation strategies.

Overall, the findings confirm that inactive mining dumps remain important sources of environmental contamination within the Jiu Valley and continue to represent a significant challenge for post-mining land management. The study provides a useful scientific basis for future monitoring programmes, rehabilitation planning and sustainable land-use decisions aimed at reducing the environmental risks associated with historical mining activities.

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