



FROM CONTAMINATION TO REMEDIATION: ENVIRONMENTAL RISK ASSESSMENT IN THE PINOASA LIGNITE QUARRY

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Abstract: Mining activities can significantly alter environmental quality by mobilizing and dispersing contaminants in soil and groundwater systems. Pinoasa Quarry, one of the major lignite open-pit mining sites in southwestern Romania, represents an area where long-term extraction activities may influence soil and water quality, potentially posing risks to ecosystems and human health. This study investigates the level of environmental contamination in the Pinoasa Quarry area through the collection and analysis of soil and water samples from locations influenced by mining activities. The research focuses on identifying potential contamination sources associated with waste rock deposits, excavated material storage areas, and mine water discharges. Laboratory analyses target key physicochemical parameters and concentrations of potentially toxic metals in order to evaluate the degree of environmental contamination. The obtained results are interpreted in relation to environmental quality standards and regulatory threshold values, providing an initial assessment of potential risks to human health and the surrounding environment. By integrating field sampling with environmental assessment, the study contributes to a better understanding of the environmental impact of lignite mining operations in the Pinoasa area. The findings support the development of informed monitoring strategies and sustainable environmental management practices for mining-affected sites, contributing to ongoing efforts aimed at mitigating environmental risks and promoting responsible resource exploitation in post-industrial landscapes.

Keywords: Mining-impacted sites; Soil contamination; Groundwater quality; Heavy metals; Environmental risk assessment; Pinoasa Quarry

1. Introduction

Mining activities represent one of the most significant sources of environmental pressure, having the capacity to profoundly alter the structure and functionality of natural ecosystems. Lignite extraction in open-pit quarries involves the removal of large volumes of soil and rock, leading to the disruption of the natural balance of environmental components, particularly soil and groundwater. In this context, the mobilization and dispersion of contaminants, including potentially toxic metals, become inevitable processes, with direct implications for environmental quality and human health.[1]

The Pinoasa Quarry area, located in southwestern Romania, represents a relevant example of a site affected by long-term intensive mining activities. Excavation processes, waste rock deposition, and mine water discharge can generate multiple sources of contamination, contributing to changes in the physicochemical properties of soil and water. Furthermore, the interaction between excavated materials and environmental factors such as precipitation and temperature variations may accelerate the release and transport of pollutants into the surrounding environment.

Environmental risk assessment in such areas becomes essential for understanding the degree of impact and for supporting the development of effective remediation and sustainable management measures. The analysis of soil and groundwater contamination provides relevant information regarding the distribution and concentration of hazardous substances, as well as their potential effects on ecosystems and human health. In

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particular, heavy metals are of significant concern due to their persistence in the environment and their capacity for bioaccumulation [2, 3, 4, 5].

The present study aims to investigate the level of environmental contamination in the Pinoasa Quarry area through the analysis of soil and water samples collected from representative locations influenced by mining activities. The research focuses on identifying the main sources of pollution, particularly those associated with waste rock deposits, excavated material storage areas, and discharged mine water. In this regard, laboratory analyses target both physicochemical parameters and the concentrations of potentially toxic metals relevant for assessing environmental quality.

The obtained results are interpreted in relation to environmental quality standards and regulatory threshold values, allowing for a preliminary assessment of the risks associated with the identified contamination. By correlating experimental data with the existing regulatory framework, the study contributes to highlighting the extent of the environmental impact caused by mining activities and to identifying areas with potentially elevated risk [6, 7].

The importance of this approach lies in providing relevant information for the development of monitoring strategies and the implementation of sustainable management practices for mining-affected sites. In the current context of the transition towards a sustainable development model, the assessment and mitigation of environmental risks associated with natural resource exploitation have become essential priorities. Thus, the study conducted in the Pinoasa area aligns with broader efforts aimed at environmental protection and the promotion of responsible mineral resource exploitation.

2. Materials and Methods

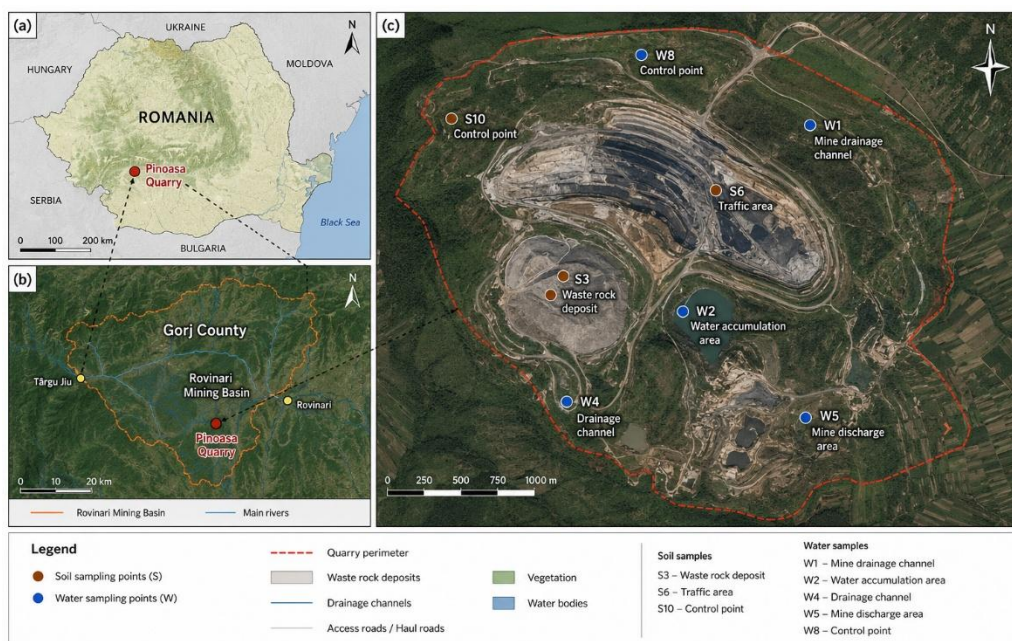


Fig. 1. Location of soil and water sampling points within the Pinoasa lignite quarry area. (a) Location of Pinoasa Quarry within Romania; (b) location within the Rovinari Mining Basin, Gorj County; (c) distribution of soil and water sampling points in relation to the main quarry features

The study was conducted within the perimeter of the Pinoasa lignite quarry, located in southwestern Romania, an area representative of surface mining operations that can generate significant alterations to environmental components. The selection of the study area was based on the intensity of excavation activities, the presence of waste rock deposits, and the existence of mine water drainage and discharge systems, all of which constitute potential sources of soil and water contamination. The investigation was designed to capture both the spatial distribution of contaminants and their temporal variability, influenced by seasonal environmental conditions.

Sampling campaigns were carried out over an extended period between May 2024 and September 2025, comprising four distinct field campaigns corresponding to the spring and autumn seasons of each analyzed year. This approach enabled the assessment of the influence of climatic factors, such as precipitation and temperature variations, on the mobilization and transport of contaminants within the environment. During each campaign, a total of ten soil sampling points and eight water sampling points were investigated. These locations

were selected based on field observations and their proximity to anthropogenic pollution sources. The sampling network included areas situated near waste rock deposits, active excavation zones, machinery traffic routes, drainage channels, and mine water accumulation points, as well as a control point located outside the direct influence of mining activities, used for comparative purposes.[8]

The relative location of the selected sampling points is presented in Figure 1. The monitoring network was designed to cover the main environmental compartments potentially affected by mining activities, including waste rock deposits, drainage channels, mine water accumulation areas, traffic routes and reference locations outside the direct influence of the quarry. Soil sampling points were coded as S3, S6 and S10, while water sampling points were coded as W1, W2, W4, W5 and W8.

Soil samples were collected from the surface layer (0–20 cm), which is considered the most sensitive to anthropogenic influence. At each location, multiple subsamples were collected and subsequently homogenized to obtain a representative composite sample. The samples were stored in polyethylene containers, properly labeled, and transported under controlled conditions to the laboratory. Prior to analysis, the samples were air-dried at room temperature, ground, and sieved to ensure homogeneity and reproducibility of the analytical results.

Water samples were collected from surface sources, including drainage channels and temporary accumulations, as well as from points directly influenced by mine water discharge. Sampling was performed using polyethylene containers, and for metal analysis, the samples were preserved by acidification with nitric acid to a pH lower than 2, in accordance with standard procedures. This step was essential to prevent metal precipitation and to maintain the chemical stability of the samples until analysis.

Laboratory analyses focused on determining a relevant set of physicochemical parameters and concentrations of potentially toxic metals in both soil and water samples. For soil samples, parameters such as pH, determined in a soil–water suspension, and organic matter content, assessed by the loss-on-ignition method, were analyzed. For both soil and water, concentrations of iron (Fe), manganese (Mn), lead (Pb), zinc (Zn), and copper (Cu) were determined, as these elements are commonly associated with mining activities and are known for their environmental impact.

Metal concentrations were determined using specific instrumental techniques following sample preparation procedures that included acid digestion with a mixture of mineral acids. Analyses were performed using Atomic Absorption Spectrometry (AAS), a widely recognized method for its accuracy and sensitivity in detecting trace metal concentrations. For water samples, additional parameters such as pH and electrical conductivity were measured using calibrated instruments, providing an overall characterization of water quality.

To ensure data quality, specific quality control measures were implemented, including the use of blank samples, calibration with standard solutions, and duplicate analyses for a representative proportion of samples. The obtained data were processed using descriptive statistical methods, including the calculation of mean values and variability for each analyzed parameter. [9, 10]

The interpretation of results was carried out by comparing the measured concentrations with the limit values established by national legislation and European standards for soil and water quality. Additionally, a pollution index was used to assess the degree of contamination, calculated as the ratio between the measured concentration and the maximum allowable value, enabling the classification of contamination levels. The adopted methodology provides a coherent and applicable framework for evaluating the impact of mining activities on the environment and constitutes a solid basis for the analysis of results and the formulation of conclusions regarding the risks associated with contamination in the studied area.

3. Results and Discussion

The analysis of water physicochemical parameters reveals clear differences between sampling points influenced by mining activities and the control location. The pH values indicate slightly acidic conditions in drainage channels and mine water accumulation areas, ranging between 5.7 and 6.0, while the control point shows near-neutral values around 7. Electrical conductivity values are significantly higher in impacted areas, exceeding 1200 $\mu\text{S}/\text{cm}$, compared to approximately 450–470 $\mu\text{S}/\text{cm}$ at the control point. These results suggest an increased level of dissolved ions, most likely originating from the weathering and leaching of mining-related materials.

Table 1. Physicochemical parameters of water samples (2024–2025)

Sampling Point	Period	pH	Electrical Conductivity (µS/cm)
W1	May 2024	6.5	820
W1	Oct 2024	6.3	910
W1	Apr 2025	6.7	780
W1	Sep 2025	6.4	860
W4 (drainage)	May 2024	5.9	1100
W4	Oct 2024	5.7	1250
W4	Apr 2025	6.0	1050
W4	Sep 2025	5.8	1180
W8 (control)	May 2024	7.2	450
W8	Sep 2025	7.1	470

The concentrations of metals in water samples indicate a clear influence of mining activities, particularly in areas affected by mine water discharge. Iron and manganese show the highest concentrations among the analyzed elements, reaching values of up to 2.5 mg/L for Fe and 1.3 mg/L for Mn in drainage zones. These elements are characteristic of lignite mining environments and are commonly associated with oxidation and leaching processes of mineral components. Lead, zinc, and copper exhibit moderate variations, with higher concentrations recorded in impacted areas, while significantly lower values are observed at the control point, indicating background levels.

Table 2. Heavy metal concentrations in water samples (mg/L)

Sampling Point	Period	Fe	Mn	Pb	Zn	Cu
W2	May 2024	1.8	0.9	0.03	0.12	0.05
W2	Oct 2024	2.2	1.1	0.04	0.15	0.06
W2	Apr 2025	1.6	0.8	0.02	0.10	0.04
W5	Sep 2025	2.5	1.3	0.05	0.18	0.07
W8 (control)	Sep 2025	0.4	0.2	0.01	0.05	0.02

Temporal variations indicate slightly higher concentrations during autumn campaigns, particularly in October 2024 and September 2025. This trend can be explained by increased precipitation, which enhances the mobilization and transport of contaminants through surface runoff and infiltration processes.

The analysis of soil samples highlights significant variations in metal concentrations depending on the location of sampling points and their exposure to mining activities. The highest values were recorded near waste rock deposits and in areas with intense machinery traffic, where the accumulation and redistribution of contaminated particles are more pronounced. Iron and manganese show consistently high concentrations across all sampling points, reflecting the geochemical characteristics of lignite-bearing formations and excavated materials.

Lead and zinc concentrations are notably higher in impacted areas, reaching maximum values of approximately 70 mg/kg for Pb and 150 mg/kg for Zn, while significantly lower values are observed at the control site. Copper shows moderate variability, without major exceedances, but with a tendency to increase in areas subjected to anthropogenic influence. These patterns suggest a direct contribution of mining operations to soil contamination.

Table 3. Heavy metal concentrations in soil samples (mg/kg)

Sampling Point	Period	Fe	Mn	Pb	Zn	Cu
S3 (waste)	May 2024	32000	850	65	140	55
S3	Oct 2024	33500	900	70	150	60
S3	Apr 2025	31000	820	60	135	52
S6 (traffic)	Sep 2025	29000	780	55	120	48
S10 (control)	Sep 2025	21000	500	25	70	30

Seasonal variations in soil composition indicate slightly higher metal concentrations during autumn, likely due to enhanced deposition and redistribution of fine particles following precipitation events and mechanical disturbances. The clear differences between impacted and control sites confirm that the observed changes in soil composition are primarily associated with mining activities rather than natural background conditions.

Overall, the results indicate a moderate level of environmental impact in the Pinoasa Quarry area, with localized zones exhibiting higher contamination levels, particularly in relation to iron, manganese, lead, and zinc. The observed spatial and temporal patterns highlight the influence of mining operations on both water and soil quality and emphasize the importance of continuous monitoring and the implementation of appropriate environmental management measures.

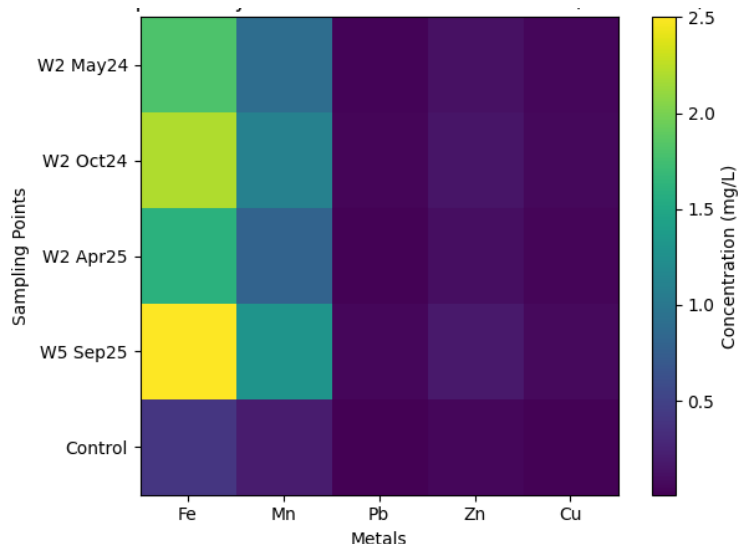


Fig. 2. Heatmap representation of heavy metal concentrations in water samples (2024–2025)

The figure 2 provides a comparative visualization of heavy metal concentrations across different sampling points and monitoring periods. Higher intensity values are observed for iron and manganese in impacted areas, particularly in W5 (September 2025), confirming the influence of mining activities. In contrast, the control sample exhibits significantly lower concentrations for all analyzed elements. The graphical representation highlights differences between sampling locations and monitoring periods, emphasizing temporal variability and the influence of mining activities on water quality.

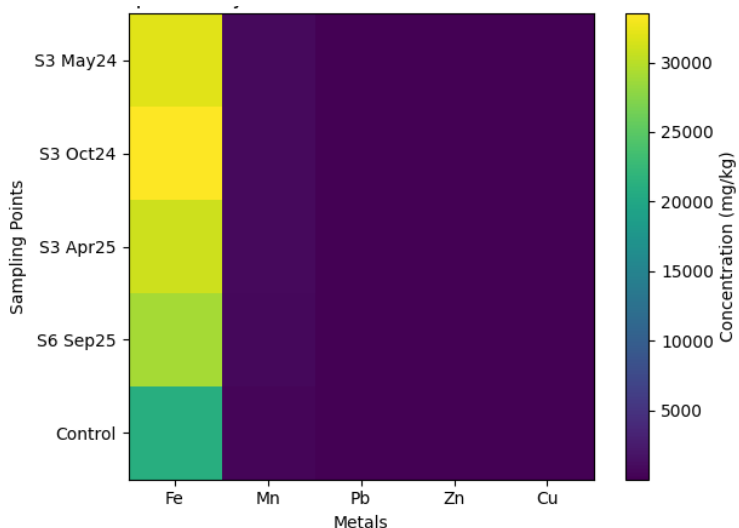


Fig. 3. Heatmap representation of heavy metal concentrations in soil samples (2024–2025)

The heatmap visualization of soil samples provides a comparative representation of heavy metal concentrations measured at different sampling locations and monitoring periods. The figure illustrates temporal variability and differences between impacted and control sites rather than a true spatial distribution of contaminants. Elevated concentrations of iron and manganese are observed in all samples collected from areas affected by mining activities, while the highest values of lead and zinc are recorded at sampling point S3, located near waste rock deposits. The measurements obtained from S3 during May 2024, October 2024 and April 2025 illustrate the temporal evolution of metal concentrations at the same location. In contrast, the control sample (S10) exhibits substantially lower concentrations for all analyzed elements, confirming the influence of mining activities on soil quality.

4. Conclusions

The integrated analysis of the obtained data indicates that the studied area is characterized by a clear influence of mining activities on environmental quality, reflected in alterations of the geochemical balance of both soil and water. The identified patterns reveal a heterogeneous distribution of contaminants, with higher concentrations occurring in areas directly exposed to extraction and waste deposition processes. The monitoring network allowed the identification of localized contamination hotspots associated with waste rock deposits, drainage channels and mine water discharge areas, confirming the spatial heterogeneity of environmental pressures within the quarry perimeter.

The findings suggest that the dominant mechanisms driving contamination are related to the interaction between excavated materials and environmental factors, particularly water, which acts as a transport medium for metallic elements. Consequently, contaminant mobility is controlled not only by the pollution sources themselves, but also by hydrological and climatic conditions, explaining the spatial and temporal variability observed throughout the monitoring period.[11]

From a risk assessment perspective, the measured values indicate the presence of moderate environmental pressures, without evidence of widespread critical exceedances. However, the tendency for localized accumulation and the persistence of certain metals highlights the need for a precautionary approach aimed at preventing long-term environmental degradation.

A relevant aspect is the clear differentiation between impacted and non-impacted areas, confirming the localized nature of the environmental impact and providing a solid basis for identifying priority zones for intervention. This spatial distribution supports the efficient targeting of monitoring and management efforts.

In the current context, the results emphasize the necessity of adopting integrated management strategies for mining-affected sites, combining continuous environmental monitoring with measures aimed at limiting contaminant dispersion. Furthermore, the study underlines the importance of correlating field data with detailed risk assessments in order to support the development of site-specific remediation solutions.

Through the adopted approach, this research contributes to a better understanding of contamination processes in lignite mining environments and provides a useful framework for promoting sustainable practices in the management of mineral resources and their associated environmental impacts.

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