Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

Application of Passive and Active Remediation Methods in the Treatment of Areas Contaminated by Acid Mine Drainage

Gabriel ***WITTENBERGER***[1], ***Martin KONČEK***[2], ***Miroslav BETUŠ***[3]*, ***Ivanna BETUŠOVÁ***[4] *and* ***Kristína HORIZRALOVÁ***[5]

Authors' affiliations and addresses:
[1] Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
e-mail: gabriel.wittenberger@tuke.sk

[2] Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
e-mail: martin.koncek@tuke.sk

[3] Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
e-mail: miroslav.betus@tuke.sk

[4] Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
e-mail: ivanna.betusova@tuke.sk

[5] Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia
e-mail: kristina.horizralova@tuke.sk

***Correspondence:**
Miroslav Betuš, Technical University Košice, FBERG, Letná 9, 04002 Košice, Slovakia.
tel.: +421 55 6023150
e-mail: miroslav.betus@tuke.sk

Acknowledgement:
This work is supported by the Scientific Grant Agency of the Ministry of Education, Science, Research, and Sport of the Slovak Republic and the Slovak Academy Sciences as part of the research projects VEGA: 1/0431/25: "Research and development of new methods based on the principles of modelling, logistics and simulation in solving technological and environmental problems with regard to the economic efficiency and safety of raw material extraction", as part of the research project VEGA 1/0039/24: " Research into the rock drilling process using acoustic-vibration signal monitoring to increase the efficiency of mineral extraction".

How to cite this article:
Wittenberger, G., Konček, M., Betuš, M., Betušová, I. and Horizralová, K. (2026) Application of Passive and Active Remediation Methods in the Treatment of Areas Contaminated by Acid Mine Drainage. *Acta Montanistica Slovaca,* Volume 31 (1), 224-235

DOI:
https://doi.org/10.46544/AMS.v31i1.17

Abstract

Remediation of areas affected by acid mine drainage (AMD) remains a persistent environmental and technical challenge, particularly in regions with a long history of mining. AMD is characterized by low pH and elevated concentrations of dissolved metals and sulfates, leading to long-term degradation of soil and water environments.

This paper evaluates selected remediation approaches applied under the geological and hydrogeological conditions of the Slovak Republic. The study is based on laboratory experiments, field investigations, and pilot-scale systems implemented at sites with different types of contamination. Special attention is given to passive treatment systems, including anoxic limestone drains, anaerobic bioreactors, and constructed wetlands, as well as selected active remediation techniques.

The results confirmed high metal removal efficiency in passive systems, with some cases exceeding 95%, particularly for iron and selected trace elements. In contrast, sulfate reduction proved to be the main limiting factor, strongly influenced by hydraulic retention time, substrate composition, and operational stability. The findings highlight both the potential and limitations of passive and active approaches and emphasize the importance of appropriate system design and optimized hydraulic conditions for long-term remediation effectiveness.

Keywords

acid mine drainage; remediation; passive remediation systems; environmental hazards; mining activities.

Introduction

Historical mining activities represent a significant source of environmental burdens that often persist for decades after extraction ceases. One of the most serious consequences of mining operations is the formation of acid mine drainage (AMD), typically characterized by low pH values and elevated concentrations of dissolved metals and sulfates. AMD is primarily generated by the oxidation of sulfide minerals when exposed to oxygen and water, triggering a series of geochemical reactions that lead to acid production and enhanced metal mobility.

As a result, these waters constitute a long-term source of contamination affecting surface and groundwater resources, soils, and surrounding ecosystems in the broader vicinity of former mining sites. The environmental impacts associated with mining activities and abandoned mines have been documented in numerous regions worldwide, with their extent largely dependent on local geological conditions, the type and intensity of mining, and the effectiveness of post-mining land reclamation measures (Matschullat & Gutzmer, 2012; Liu et al., 2021; Gaćina & Dimitrijević, 2022).

Negative environmental impacts associated with acid mine drainage have been documented in numerous mining regions worldwide, with their intensity strongly influenced by the lithological composition of host rocks and the prevailing geochemical conditions (Jamaluddin et al., 2023). The mineralogical characteristics of the rock mass, together with hydrological and climatic factors, largely determine the rate of sulfide oxidation and the subsequent release of acidity and metals into the surrounding environment.

Contamination of surface waters, stream sediments, and biotic components of ecosystems by AMD has been confirmed by multiple studies, highlighting the combined chemical and ecotoxicological effects of dissolved metals and sulfates (Alvarenga et al., 2021). These impacts are often manifested not only in deteriorated water quality but also in altered biological communities and reduced ecological resilience.

The remediation of AMD-affected waters, therefore, represents both a technical and an economic challenge. In addition to the primary treatment processes, secondary environmental outputs may also arise, such as sludge generated during AMD treatment, which requires further handling and management (Amanda & Moersidik, 2019). Consequently, effective remediation strategies must consider not only treatment efficiency but also the long-term sustainability and environmental implications of by-products generated during the process.

Depending on geological, hydrogeological, and climatic conditions, various remediation approaches are applied, which can generally be classified into active and passive methods. Active treatment systems are typically based on chemical neutralization and engineered water treatment processes, including the dosing of alkaline reagents, aeration, sedimentation, and subsequent sludge handling. These methods are often effective in rapidly reducing acidity and metal concentrations; however, they require continuous operation, energy input, and regular maintenance.

In contrast, passive remediation systems rely on naturally occurring geochemical and biological processes taking place within constructed treatment units. Such systems include anoxic limestone drains (ALD), anaerobic bioreactors, and constructed wetlands. Their functioning is based on neutralization reactions, metal precipitation, and microbial sulfate reduction, all occurring under controlled but largely self-sustaining conditions. Passive systems are generally considered more suitable for long-term treatment of stabilized flows, particularly where operational simplicity and reduced maintenance requirements are desired.

In recent decades, increasing attention has been devoted to passive remediation systems, which are generally characterized by lower operational costs, reduced maintenance requirements, and improved long-term sustainability compared to conventional active treatment methods. Their performance is closely linked to microbial activity, particularly that of sulfate-reducing bacteria, which play a key role in sulfide formation and subsequent metal precipitation (Ly et al., 2019). The overall effectiveness of these systems, however, strongly depends on appropriate hydraulic design, sufficient retention time, the composition and biodegradability of the organic substrate, and site-specific environmental conditions (Oberholzer et al., 2022).

A particular challenge remains the removal of sulfates, which is technologically more demanding than metal removal and frequently represents the limiting factor in passive treatment efficiency. Insufficient microbial activity or unfavorable environmental conditions—such as low temperatures, inadequate carbon supply, or unstable redox regimes—may lead to incomplete sulfate reduction and thus compromise the long-term stability of the system (Ly et al., 2019).

The objective of this paper is to present and evaluate practical experience with the remediation of sites contaminated by acid mine drainage under the geological and hydrogeological conditions of the Slovak Republic. The study focuses on comparing the efficiency of selected remediation methods applied at sites affected by different types of environmental burdens, with particular emphasis on the practical outcomes of laboratory experiments, field investigations, and pilot-scale treatment systems. The knowledge gained provides a basis for optimizing remediation design and may serve as a methodological framework for addressing similar environmental problems in mining regions with comparable natural and technical conditions.

Problem Analysis

Formation and Characteristics of Acid Mine Drainage

Acid mine drainage (AMD) is primarily generated as a result of the oxidation of sulfide minerals, particularly pyrite (FeS_2), under conditions where oxygen and water are present. This process initiates a series of complex geochemical reactions that lead to the formation of sulphuric acid, which significantly lowers pH and promotes the release of metals originally bound within the mineral structures of the host rocks (Rusko et al., 2011). As a consequence, the resulting waters are typically characterized by high mineralization and elevated concentrations of dissolved metals and sulfates, exerting a pronounced negative impact on environmental quality.

The development and intensity of AMD are strongly influenced by the mineralogical composition of the rock mass and by the prevailing hydrogeochemical conditions. Factors such as permeability, groundwater flow regime, temperature, and the availability of reactive sulfide surfaces determine both the rate of sulfide oxidation and the subsequent mobility of metals. For this reason, the prediction of future water quality evolution in mining areas is frequently carried out using laboratory leaching tests and controlled experimental simulations. These approaches allow for the estimation of sulfide oxidation rates and metal release dynamics under defined conditions (Andini et al., 2024). The insights gained from such predictive assessments are essential for designing appropriate preventive and remediation measures to mitigate long-term environmental impacts in post-mining landscapes.

The intensity of AMD formation is controlled by a range of interrelated factors, including the mineralogical composition of the host rocks, the physical properties of mining wastes, the permeability of the geological environment, climatic conditions, and the hydrological regime of the area. The manner in which mining wastes are deposited also plays a crucial role. In particular, the degree of compaction and the position of waste bodies on slopes significantly influence oxygen availability and the rate of water circulation within waste heaps or tailings impoundments, thereby affecting the overall rate of sulfide oxidation (Campaner et al., 2014).

Long-term exposure to acid mine drainage results in substantial alterations to the chemical composition of aquatic ecosystems and has pronounced effects on biological communities. These impacts are reflected, for example, in changes in diatom assemblages and the occurrence of teratological forms, which serve as indicators of environmental stress and contamination (Sienkiewicz et al., 2023). Such findings demonstrate that the influence of AMD extends beyond purely chemical contamination, resulting in broader ecological consequences and long-term disturbances to ecosystem structure and function.

Environmental Impacts of Acid Mine Drainage

Acid mine drainage constitutes a long-term source of contamination affecting surface and groundwater bodies, soils, and the biotic components of ecosystems. Low pH values combined with elevated concentrations of metals such as Fe, Al, Cu, Zn, and Mn contribute to soil degradation, damage to vegetation, and reduced biodiversity in aquatic ecosystems. Once released, contaminants may migrate over considerable distances and, in some cases, lead to secondary contamination of stream and reservoir sediments (Thiruvenkatachari et al., 2011). Such processes can extend the spatial impact of AMD far beyond the original source area.

An important aspect of environmental risk assessment is identifying pollution sources and monitoring them long-term. The integration of detailed chemical analyses with participatory monitoring approaches can enhance the effectiveness of environmental risk management in mining regions by improving data reliability and stakeholder involvement (Ruppen et al., 2021). Continuous monitoring is particularly crucial in areas where AMD discharge is persistent and subject to seasonal fluctuations.

A specific concern is the transport of sulfates, which are highly mobile in aquatic environments and difficult to remove with conventional treatment methods. Elevated sulfate concentrations in surface waters may alter overall water chemistry and promote the formation of secondary mineral phases, especially sulfide and oxyhydroxide compounds of iron and aluminum. Under acidic conditions, minerals such as jarosite and other iron-sulfate phases may form, playing a significant role in the evolution of AMD and influencing subsequent metal mobility (Murray et al., 2014).

These secondary precipitates can modify stream morphology, affect hydraulic conditions, and act as sorptive phases for additional toxic elements. The migration of contaminants within the subsurface environment is further controlled by the structural characteristics of the rock mass, fracture networks, and site-specific hydrogeological properties. For this reason, assessing contamination spread often requires a combination of geochemical modeling and geophysical methods to evaluate environmental risk adequately (Guillon et al., 2024).

Remediation Approaches for Mine Water Contamination

The remediation of areas affected by acid mine drainage is a complex environmental intervention that requires integrating technical, geochemical, and biological approaches. From an implementation perspective, remediation methods are generally classified into active and passive systems. Active treatment methods involve intensive technological interventions, such as chemical neutralization, pumping and treating contaminated water, or excavating and replacing polluted soils. Although these approaches are typically highly effective in rapidly reducing contaminant concentrations, they are financially demanding and require continuous operation, monitoring, and long-term maintenance (Nancucheo et al., 2017).

In recent years, increasing attention has been directed toward the application of sulphidogenic bacteria and biologically driven processes for the removal of metals and sulfates. These approaches represent a promising direction for developing more sustainable remediation technologies, as they enable the conversion of dissolved metals into stable sulfide phases under controlled anaerobic conditions (Nancucheo et al., 2017). At the same time, research has focused on the potential use of various waste materials - including mining residues, agro-industrial by-products, and municipal wastes - as sources of organic substrates to enhance biological sulfate reduction and metal immobilization (Aguilar Garrido et al., 2021). Such strategies not only improve treatment efficiency but may also contribute to waste valorization and to the principles of the circular economy.

Passive remediation systems rely on naturally occurring geochemical and biological processes within the geological environment or engineered ecological units. Among the most commonly applied technologies are anoxic limestone drains (ALD), anaerobic bioreactors, and constructed wetlands. Their primary advantages include lower operational costs, reduced energy consumption, and a comparatively limited physical impact on the landscape when contrasted with active treatment methods (Castro Huaman et al., 2023).

Despite these benefits, the effectiveness of passive systems is strongly influenced by local geological and hydrogeological conditions, the hydraulic regime, and the composition and biodegradability of the substrate used. A major limitation remains the reduction of sulfates, which requires stable anaerobic conditions and sufficient activity of sulfate-reducing microorganisms. If these conditions are not maintained, treatment performance may decline, particularly in systems exposed to fluctuating flows or seasonal temperature variations (Palihakkara et al., 2018).

Specific Aspects of AMD Remediation under the Conditions of the Slovak Republic

The territory of the Slovak Republic is characterized by a high number of historical mining sites, many of which represent significant and persistent environmental burdens. Geological diversity, rugged terrain, and variable climatic conditions substantially influence the behavior of acid mine drainage and the effectiveness of remediation measures. In many cases, the affected sites are located in areas with limited accessibility or complex hydrogeological settings, where large-scale active remediation interventions are technically difficult or economically impractical. Under such conditions, alternative and site-adapted solutions are required (Balintová, 2011).

Studies conducted at Slovak mining sites have revealed specific microbial communities and distinct geochemical processes in mine waters, which significantly affect their chemical composition and the potential for natural attenuation (Kisková et al., 2018). Long-term monitoring of abandoned mining areas, such as the Smolník site, confirms the persistent impact of AMD on the aquatic environment and underscores the need for systematic, sustained remediation measures (Demčák et al., 2020).

For these reasons, passive treatment systems are increasingly applied in practice, as they enable long-term reduction of environmental risks at relatively moderate operational costs. However, experience from implemented remediation projects indicates that each locality requires an individual approach. Thorough assessment of geological and hydrogeological conditions, together with careful optimization of system design, is essential to ensure long-term functionality, hydraulic stability, and overall treatment efficiency.

Material and Methods

Site Selection and Methodological Approach

The study was based on data obtained from laboratory experiments, field trials, and pilot-scale remediation systems implemented at selected sites affected by acid mine drainage within the territory of the Slovak Republic. The selection of localities reflected differences in geological structure, hydrogeological conditions, and technological context, as well as the availability of long-term monitoring data. This approach enabled assessment of remediation performance across varied environmental and operational conditions.

The methodological framework combined experimental investigations with practical, application-oriented procedures. In the initial phase, laboratory-scale tests were carried out to verify the suitability of selected substrates and technological configurations for AMD treatment. These controlled experiments enabled evaluation of neutralization capacity and metal removal potential, and the development of redox conditions under defined parameters.

Subsequently, the laboratory findings were validated under real environmental conditions through pilot-scale remediation systems installed directly at the selected sites. The effectiveness of individual remediation methods was assessed based on changes in key physicochemical parameters of the treated waters, providing a comprehensive evaluation of treatment performance and system stability.

Applied Analytical Methods

Water samples were collected at regular intervals throughout both the laboratory experiments and the field trials. In situ measurements focused on basic physicochemical parameters, particularly pH, temperature, electrical conductivity, and redox potential (Eh), as these indicators provide immediate insights into chemical stability and reaction dynamics within the treatment systems.

Laboratory analyses were conducted to determine the concentrations of the principal contaminants typically associated with acid mine drainage, namely Fe, Al, Cu, Zn, Mn, Ca, and sulfates. These parameters were selected to enable a comprehensive assessment of both metal removal efficiency and the evolution of sulfate concentrations during the treatment process.

All analyses were performed in accredited laboratories using standard analytical procedures applicable to environmental water samples. The obtained data were processed and evaluated by comparing influent and effluent concentrations of the monitored parameters within each remediation system. This comparative approach enabled quantification of treatment efficiency and facilitated interpretation of geochemical and biological processes during remediation.

Banská Štiavnica – Šobov Site

Site characteristics: The Šobov locality is situated north of the town of Banská Štiavnica and is characterized by a waste heap formed after quartzite extraction, together with a quarry containing sulfide mineralization. The geological setting is dominated by quartzite, with pyrite and clay minerals present. The relatively high permeability of the waste material promotes the infiltration of oxygenated water, creating favorable conditions for sulfide oxidation and the subsequent formation of acid mine drainage. These processes have a negative impact on the surrounding environment, including soil microbial communities, which are particularly sensitive to acidification and changes in geochemical balance (Balogová et al., 2025).

The fundamental geological and hydrogeological conditions of the site are schematically illustrated in Fig. 1, providing an overview of the structural configuration, groundwater flow patterns, and potential zones of AMD generation and migration.

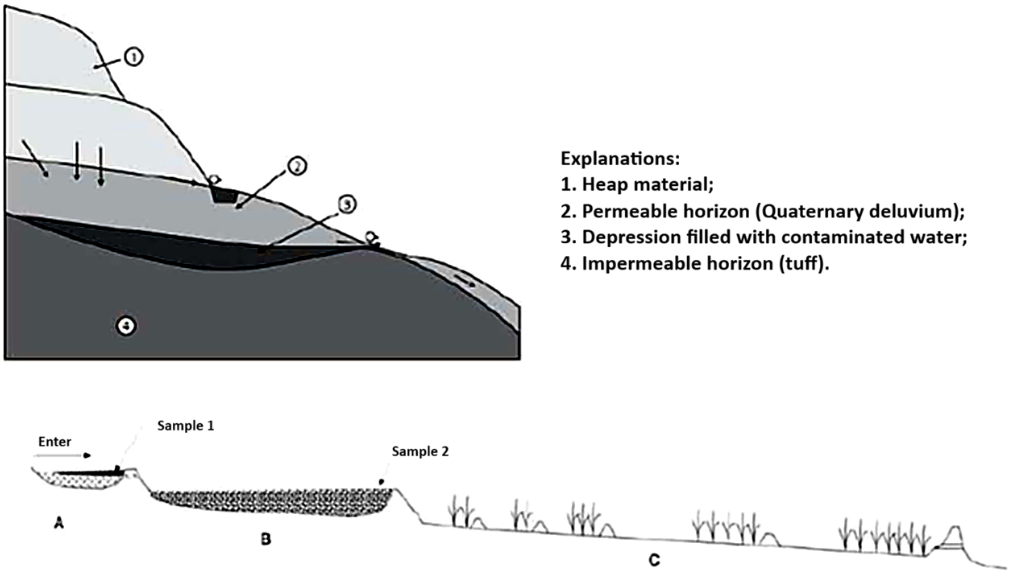

Fig. 1. Geological and Hydrogeological Conditions of the Banská Štiavnica – Šobov Site

Tab. 1 Chemical Parameters of Acid Mine Water at the Inlet and Outlet of the Šobov Remediation System

Parameter	Unit	Inlet	Outlet 1 (ALD)	Outlet 2 (Anaerobic Section)
pH	[-]	2,1 – 2,4	4,5 – 5,5	6,2 – 6,8
Eh	[mV]	500 – 600	150 – 250	-80 až -20
Fe	[mg·l^{-1}]	2260	54,1	39,6
Al	[mg·l^{-1}]	900	0,4	0,2
Mn	[mg·l^{-1}]	51	32,6	23
Cu	[mg·l^{-1}]	4,95	0,03	0,03
Ca	[mg·l^{-1}]	248	–	630

Laboratory Experiments: The laboratory experiments were conducted in closed plastic containers with a volume of 7 L, filled with a substrate composed of a mixture of cattle manure and crushed limestone. The substrate was saturated with acid mine water collected directly from the site. The objective of the experiments was to assess the system's ability to increase pH and reduce metal concentrations under varying temperature conditions.

Water samples were collected at regular intervals throughout the experiment, while the volume of inflowing water was gradually increased to simulate changing hydraulic conditions. Measurements of pH, temperature, and redox potential (Eh) were continuously recorded, and concentrations of selected elements were determined weekly. The laboratory phase of the experiment lasted a total of 565 days.

Field Trials and Pilot Remediation System: Based on results from the laboratory experiments, field trials were subsequently conducted on-site. A 150 L barrel filled with a substrate consisting of limestone, manure, straw, and sawdust was used as the testing unit. The system was regularly supplied with acid mine water and monitored to evaluate treatment efficiency.

The pilot remediation system was designed as a combination of an anoxic limestone drain, an anaerobic treatment stage, and an aerobic stage incorporating a constructed wetland. A schematic representation of the pilot system is presented in Table 1. The system's efficiency was evaluated by comparing the water's chemical composition at the inlet and outlet of the treatment system.

Smolník Site

Site characteristics: The Smolník locality represents one of the most significant environmental burdens resulting from historical polymetallic ore mining in the Slovak Republic. Abandoned mine workings and tailings impoundments constitute a long-term source of acid mine drainage, which adversely affects the quality of surface waters within the Smolník Creek catchment (Lintnerová et al., 2008). Ongoing geochemical processes in sediments, together with the formation of secondary iron minerals, confirm the persistence of intensive acidification and oxidation reactions in this area (Dakos et al., 2012). These processes contribute to sustained metal mobility and long-term contamination of the aquatic environment.

Laboratory and field experiments: Laboratory-scale tests were conducted in containers containing substrates of varying composition, including limestone, manure, sawdust, and straw in different proportions. These experiments were designed to assess the influence of substrate composition on neutralization capacity and metal removal efficiency.

Subsequently, field trials were conducted using approximately 150 L barrels to evaluate the impact of flow rate on remediation efficiency. The composition of the individual substrates used in the field experiments is presented in Tab. 2. The substrates comprised varying ratios of limestone, sawdust, straw, and manure, and differences in composition were reflected in variations in metal removal performance, underscoring the importance of substrate optimization for effective treatment.

Tab. 2 Substrate Composition Applied in Field Trials – Smolník Locality

Substrate Component	Barrel 1 [%]	Barrel 2 [%]	Barrel 3 [%]	Barrel 4 [%]
Limestone	50	20	30	50
Aged sawdust	30	60	30	30
Fresh sawdust	0	0	0	30
Straw	10	10	30	30
Manure	10	10	10	10
Total volume of applied AMD [L]	[L] 106	67	147	175

Pilot Remediation System: The pilot remediation system at the Smolník site was constructed as a built wetland with an unconventional water-inflow arrangement. This design enabled evaluation of the influence of hydraulic retention time on the efficiency of metal and sulfate removal under site-specific conditions. The modified inflow configuration allowed controlled variation of flow dynamics and improved assessment of treatment performance.

The results obtained from monitoring the pilot system are presented in Table 3

Tab. 3 Average Values of Acid Mine Water Parameters at the Inlet and Outlet of the Smolník Pilot System (25 May – 26 September 2018)

Parameter	Unit	Inlet	Outlet
pH	[-]	3,36	5,64
SO_4^{2-}	$[mg \cdot l^{-1}]$	3652	3273
Ca	$[mg \cdot l^{-1}]$	214,5	537
Fe	$[mg \cdot l^{-1}]$	573	378
Al	$[mg \cdot l^{-1}]$	133,2	7,83

Parameter	Unit	Inlet	Outlet
Cu	[mg·l^{-1}]	5,19	0,048
Zn	[mg·l^{-1}]	17,75	1,03
Mg	[mg·l^{-1}]	399,5	391,3
Mn	[mg·l^{-1}]	41,83	39,82
Eh	[mV]	347,3	-168,6
Electrical conductivity	[mS·m^{-1}]	384	376
Dissolved solids	[mg·l^{-1}]	6217	5690

The schematic diagram of the pilot passive remediation system is shown in Fig. 2.

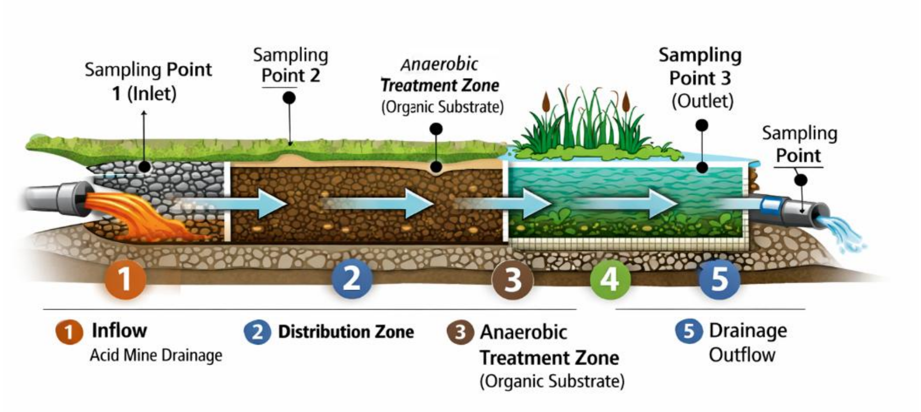

Fig. 2. Schematic cross-section of the pilot passive remediation system at the Smolník site, indicating the inflow of acid mine water, the distribution zone, the anaerobic zone containing the organic substrate, the wetland section, the drainage outlet, and the sampling points.

Krompachy Site

Contamination characteristics: At the premises of VSE, a.s., in Krompachy, contamination of soils and groundwater by petroleum substances originating from transformer oils was identified. The contamination was localized in several source zones with varying depths, in some cases extending down to the saturated zone. The Krompachy area has long been affected by industrial activities, and landscape transformation, as well as changes in soil conditions have been documented in several studies (Michaeli et al., 2017). Ecotoxicological assessments conducted in the region have confirmed the presence of contaminants and elevated environmental risks in certain parts of the area (Šestinová et al., 2016; Šestinová et al., 2020).

Applied remediation methods: The remediation was carried out using a combination of in situ and ex situ techniques. These included excavation and removal of contaminated soils, pump-and-treat remediation of groundwater, and flushing of the geological environment with the addition of anionic surfactants to enhance the mobilization of petroleum hydrocarbons. The effectiveness of the remediation measures was evaluated based on changes in the concentrations of petroleum hydrocarbons in soils and groundwater, allowing assessment of contaminant reduction and overall site stabilization.

Results

Banská Štiavnica – Šobov Site

Efficiency of the Pilot Passive System: At the Šobov site, the performance of the pilot remediation system was evaluated by comparing the chemical composition of acid mine water at the system inlet and at the outlets of its individual treatment stages. The principal inlet and outlet values are presented in Table 1.

At the system inlet, pH ranged from 2.1 to 2.4, while Fe concentrations reached 2,260 mg·L^{-1} and Al concentrations were approximately 900 mg·L^{-1}. After passing through the anoxic limestone drain, a substantial increase in pH (4.5–5.5) was observed, accompanied by a marked decrease in Fe concentration to 54.1 mg·L^{-1}. Within the anaerobic section of the system, pH further increased to 6.2–6.8, and Fe concentration declined to 39.6 mg·L^{-1}.

The overall Fe removal efficiency reached approximately 98%, representing a significant improvement in water quality. A similar trend was observed for Al, whose concentration at the system outlet decreased to around 0.2 mg·L^{-1}, corresponding to an approaching 100% removal efficiency.

In the case of Cu, concentrations declined from approximately 4.95 mg·L^{-1} to 0.03 mg·L^{-1}, indicating removal efficiency exceeding 99%. In contrast, Mn exhibited a lower degree of reduction, with concentrations decreasing by roughly 50%.

Sulfate Reduction: Sulfate concentrations in the influent ranged between 6,000 and 12,000 mg·L⁻¹. In the anaerobic section, concentrations decreased to approximately 2,300–3,000 mg·L⁻¹. Although this represents a substantial reduction, sulfate removal efficiency was significantly lower than that observed for metals, generally ranging from 50% to 70% depending on operational conditions.

The results confirm that sulfate reduction is strongly influenced by hydraulic retention time and the intensity of biological reduction processes within the anaerobic environment.

Smolník Site

Laboratory and field experiments: Laboratory tests demonstrated the capacity of the applied substrates to raise the pH of acid mine water from an initial value of 3.82 to 5.81 - 6.02. These results confirmed the neutralization potential of the limestone-based mixtures under controlled conditions.

Subsequent field trials conducted in 150 L barrels further verified the effectiveness of the passive treatment approach. Differences in performance were observed depending on substrate composition and the volume of flowing water. The most favorable results were achieved in the system where the inflow volume was gradually increased, allowing progressive adaptation of the biochemical processes within the substrate. In the final phase of the experiment, Fe removal efficiency reached 96 - 97%, whereas in systems with less favorable substrate composition, efficiency was approximately 78%.

The removal of Cu and Zn was highly effective, with efficiencies around 99%, indicating strong immobilization of these metals under the prevailing treatment conditions. The composition of the applied substrates and the principal operational parameters are presented in Table 2.

Pilot system at Smolník: Monitoring of the pilot-scale system (Table 3) showed a pH increase from 3.36 to 5.64, reflecting partial neutralization of the influent water. The concentration of Al decreased from 133.2 mg·L⁻¹ to 7.83 mg·L⁻¹, and Cu from 5.19 mg·L⁻¹ to 0.048 mg·L⁻¹. Zn concentrations declined from 17.75 mg·L⁻¹ to 1.03 mg·L⁻¹.

In contrast, Fe concentration decreased only from 573 mg·L⁻¹ to 378 mg·L⁻¹, representing relatively low removal efficiency compared to the Šobov site. Sulfate reduction was minimal, with concentrations declining from 3,652 mg·L⁻¹ to 3,273 mg·L⁻¹.

These results suggest that the structural design of the pilot system significantly influenced hydraulic retention time and, consequently, the efficiency of reduction processes occurring within the treatment unit.

Krompachy Site

During the remediation of petroleum contamination, a significant reduction in concentrations of non-aqueous extractable hydrocarbons (NEL) was recorded in groundwater. In one of the identified source zones, concentrations decreased from approximately 13 mg·L⁻¹ to values in the range of hundredths to tenths of mg·L⁻¹. In a second source zone, concentrations declined to approximately 1.38 mg·L⁻¹, indicating substantial contaminant removal, although residual pollution remained locally present.

Excavation of contaminated soils resulted in the complete removal of shallow contamination hotspots. For deeper contamination extending into the saturated zone, the combination of groundwater pump-and-treat remediation and flushing of the geological environment with surfactants proved effective. This integrated approach enhanced the mobilization and subsequent extraction of petroleum hydrocarbons from the porous medium, resulting in a measurable reduction in contaminant mass in both soil and groundwater.

Discussion

Comparison of Passive System Efficiency

The results obtained at the Šobov and Smolník sites confirm that passive remediation systems are an effective tool for removing metals from acid mine drainage. At the Šobov site, high removal efficiencies were achieved for Fe, Al, and Cu. Iron removal exceeded 95%, while Al and Cu concentrations were reduced to values approaching complete removal. A comparable trend was observed in the laboratory and field experiments conducted at Smolník, where Cu and Zn removal efficiencies reached approximately 99%, indicating strong immobilization of these metals under suitable treatment conditions.

Differences between the two sites were particularly evident in the removal of Fe and sulfates. At Šobov, a substantial decrease in Fe concentration was already observed in the anoxic limestone drain, whereas the pilot system at Smolník exhibited lower Fe removal efficiency. This discrepancy can be attributed to differences in system design and shorter hydraulic retention time in the Smolník installation.

The findings suggest that hydraulic configuration, sufficient retention time, and effective flow control are decisive in establishing stable reducing conditions and efficiently neutralizing acid mine waters (Neculita et al., 2007). Proper system design is therefore essential for achieving consistent long-term treatment performance in passive remediation systems.

Geochemical Mechanisms of Contaminant Removal

The efficiency of passive remediation systems is governed by a combination of geochemical and biological processes occurring within the reactive medium. In systems containing limestone, neutralization reactions occur between $CaCO_3$ and sulphuric acid produced by sulfide oxidation. This interaction increases pH and forms bicarbonate ions. The subsequent rise in pH promotes the precipitation of metals as hydroxides, particularly $Fe(OH)_3$ and $Al(OH)_3$, which are insoluble under near-neutral conditions.

In the anaerobic sections of the system, biological sulfate reduction is mediated by sulfate-reducing bacteria that utilize organic substrates as energy sources. This process leads to the production of sulfide ions (S^{2-}), which react with dissolved metals to form insoluble metal sulfides such as FeS, CuS, or ZnS. This mechanism is especially important for the removal of copper and zinc, for which high removal efficiencies were observed during the experiments.

The geochemical stability of the system depends on maintaining appropriate redox conditions. An increase in flow rate or a reduction in hydraulic retention time may allow oxygen to penetrate the system, leading to the re-oxidation of sulfides and a decline in treatment efficiency. Consequently, hydraulic stability and controlled flow conditions are critical factors for ensuring the long-term functionality and performance of passive remediation systems.

Influence of Hydraulic Loading and Retention Time

A comparison of results from the Šobov and Smolník sites highlights the importance of hydraulic configuration and sufficient water retention time within the reactive medium. Hydraulic retention time represents a key parameter governing both neutralization and reduction processes, as it determines the duration of contact between contaminated water and the reactive substrate.

At the Šobov site, the system was designed to ensure relatively uniform flow conditions and adequate residence time within the treatment unit. This configuration enabled effective iron precipitation and subsequent pH stabilization. In contrast, the Smolník system exhibited shorter retention times and less controlled flow conditions, which may have limited the development of stable anaerobic environments and reduced sulfate reduction efficiency.

Hydraulic loading also affects oxygen distribution within the reactive medium. At higher flow rates, oxygen may penetrate into zones intended to remain anaerobic, thereby inhibiting the activity of sulfate-reducing bacteria and reducing the formation of metal sulfides. For this reason, stable flow conditions and uniform hydraulic distribution are critical design and operational factors in ensuring the long-term performance of passive remediation systems.

Sulfate Removal Issues

Sulfate removal proved to be a limiting factor in the overall efficiency of passive treatment systems. Although biological sulfate reduction to sulfide occurs under anaerobic conditions, the extent of this process is strongly dependent on the availability of organic substrate, temperature, and hydraulic retention time. At the Šobov site, sulfate concentrations were reduced by approximately one half to two thirds, whereas at Smolník the decrease was minimal.

The relatively low sulfate reduction efficiency observed at Smolník can be attributed to insufficient water residence time within the anaerobic environment, which likely constrained the activity of sulfate-reducing bacteria. In addition, preferential binding of sulfide to Cu and Zn may have occurred, as these metals exhibit a higher affinity for sulfide formation compared to Fe. This mechanism could have reduced the availability of dissolved sulfide for iron precipitation as iron sulfides, thereby limiting overall sulfate removal and altering the dominant pathways of metal immobilization within the system.

Influence of Geological and Hydrogeological Conditions

The results indicate a pronounced influence of local geological conditions on remediation efficiency. At the Šobov site, a relatively impermeable horizon played a significant role by limiting uncontrolled seepage and stabilizing hydraulic and geochemical conditions within the treatment system. This structural feature contributed to more stable flow patterns and supported the establishment of favorable conditions for neutralization and reduction processes.

In contrast, the Smolník system was affected by lateral inflows and unstable discharge, which reduced hydraulic control and negatively influenced treatment performance. Variability in flow conditions likely led to fluctuations in retention time and redox stability, thereby limiting the effectiveness of sulfate reduction and metal immobilization.

These findings emphasize that the design of passive remediation systems must be based on a detailed assessment of site-specific hydrogeological conditions. Ensuring adequate control of the hydraulic regime is essential for maintaining stable treatment performance and achieving long-term system reliability.

Comparison of Passive and Active Remediation Approaches

The remediation of petroleum contamination in Krompachy was implemented through a combination of active techniques, including excavation of contaminated soils and flushing of the geological environment using surfactants. Compared to passive systems used for the treatment of acid mine drainage, this approach represents a more technologically demanding but considerably faster intervention, aimed at rapid reductions in contaminant concentrations and immediate risk mitigation.

Passive systems are generally more suitable for the long-term management of stabilized contamination sources, where the objective is the gradual reduction of environmental risk while minimizing operational costs. In contrast, active methods are more effective for acute or highly concentrated contamination; however, they require a higher financial investment, a continuous supply of chemical reagents, and more intensive technical supervision (Wibowo et al., 2021).

Experimental studies further confirm that properly designed passive systems can achieve high treatment efficiency, particularly under stable hydraulic conditions that allow the development of consistent geochemical and biological processes (Noor et al., 2023). These findings underscore the importance of selecting remediation strategies according to site-specific contamination characteristics, technical feasibility, and long-term sustainability objectives.

Limitations and Recommendations for the Design of Remediation Systems

Based on the results obtained, several key conclusions can be drawn. First, metal removal efficiency in passive systems was consistently high under suitable operating conditions. Second, sulfate reduction remains a technological challenge and is often the limiting factor in overall treatment performance. Third, hydraulic retention time is a critical design parameter that directly influences both neutralization and biological reduction processes. Finally, the structural configuration of the treatment unit substantially affects its operational stability and long-term reliability.

Accordingly, the design of remediation measures should incorporate the following principles:

- optimization of the hydraulic regime to ensure stable flow conditions and adequate retention time,
- provision of sufficient and appropriately composed organic substrate to support microbial activity,
- minimization of uncontrolled inflows and hydraulic short-circuiting,
- consideration of seasonal variations, particularly temperature fluctuations and changes in discharge, which may affect system performance.

Careful integration of these factors is essential to achieve sustainable and effective long-term remediation of sites affected by acid mine drainage.

Accordingly, the design of remediation measures should:

- optimize the hydraulic regime to ensure stable flow distribution and sufficient retention time,
- provide an adequate quantity and suitable composition of organic substrate to sustain microbial activity,
- account for seasonal influences, particularly temperature variations and fluctuations in discharge, which may affect treatment performance.

Conclusions

Based on the laboratory experiments, field trials, and pilot remediation systems implemented within this study, the following conclusions can be drawn:

1. Passive remediation systems based on anoxic limestone drains, anaerobic substrates, and constructed wetlands are effective approaches for reducing metal concentrations in acid mine drainage. Under the conditions of the investigated sites, high removal efficiencies were achieved for Fe, Al, Cu, and Zn, in some cases exceeding 95%.
2. Sulfate reduction proved to be the limiting factor in the overall performance of passive systems. The success of sulfate removal depends primarily on hydraulic retention time, availability of organic substrate, and the stability of anaerobic conditions within the treatment unit.
3. The structural design of the remediation system and control of the hydraulic regime significantly influence treatment efficiency. Insufficient retention time or uncontrolled inflows may substantially reduce the effectiveness of reduction processes.
4. Active remediation techniques applied to petroleum contamination demonstrated high efficiency in addressing localized pollution hotspots; however, they require greater financial investment and more complex technological infrastructure.
5. The results underline the necessity of site-specific design of remediation measures, with particular emphasis on detailed analysis of geological and hydrogeological conditions. A combination of passive

and active approaches may provide an optimal solution depending on the nature and extent of the environmental burden.

From a practical perspective, the findings highlight the need for individualized system design tailored to contamination characteristics, hydraulic conditions, and geological structure. Passive systems are particularly suitable for stabilized and long-term pollution sources with relatively steady flow conditions, where adequate retention time and hydraulic control can be ensured.

Under conditions of fluctuating discharge or high contaminant concentrations, integrating passive components with active technological interventions may enhance system stability and the predictability of treatment performance. Hybrid systems can therefore represent a balanced compromise between economic feasibility and required remediation efficiency.

Overall, the results of this study confirm that properly designed passive systems can serve as a sustainable, long-term tool for mitigating the environmental impacts of historical mining activities in the Slovak Republic. Their successful implementation, however, requires thorough hydrogeological assessment, optimization of hydraulic parameters, and regular monitoring to ensure sustained functionality and environmental protection.

References

Aguilar Garrido, A., Martínez Garzón, F. J., Paniagua López, M., Sierra Aragón, M., Fernández Ondoño, E., & Martín Peinado, F. J. (2021). Potential of mining, agro-industrial and urban wastes for acid mine drainage remediation. *EGUsphere Conference Abstracts*. https://doi.org/10.5194/egusphere-egu21-7093

Alvarenga, P., Guerreiro, N., Simões, I., Imaginário, M. J., & Palma, P. (2021). Assessment of the environmental impact of acid mine drainage on surface water, stream sediments, and macrophytes using a battery of chemical and ecotoxicological indicators. *Water*, 13(10), 1436. https://doi.org/10.3390/w13101436

Amanda, N., & Moersidik, S. S. (2019). Characterization of sludge generated from acid mine drainage treatment plants. *Journal of Physics: Conference Series*, 1351(1). https://doi.org/10.1088/1742-6596/1351/1/012113

Andini, D. E., Irvani, Henri, Susilo, N. B., Widodo, P., & Lovina, R. V. (2024). Predicting water quality in tin mining using the free drainage column leach test. *IOP Conference Series: Earth and Environmental Science*, 1419(1), 012043. https://doi.org/10.1088/1755-1315/1419/1/012043

Balintová, M. (2015). Partial sulphate precipitation with iron oxidation in acid mine waters (Slovakia). In *SGEM 2015 Conference Proceedings*. https://doi.org/10.5593/sgem2015/b51/s20.081

Balogová, M., Šimonovičová, A., Vojtková, H., & Novák, O. (2025). The metabolic fingerprint of soil microbiota in an acidified environment using Biolog Microstation™. *Biologia*, 80(6), 1589–1603. https://doi.org/10.1007/s11756-025-01934-3

Campaner, V. P., Luiz-Silva, W., & Machado, W. (2014). Geochemistry of acid mine drainage from a coal mining area and processes controlling metal attenuation in stream waters, southern Brazil. *Anais da Academia Brasileira de Ciências*, 86(2), 539–554. https://doi.org/10.1590/0001-37652014113712

Castro Huaman, K., Vasquez Olivera, Y., Aramburu Rojas, V., Arauzo, L., Raymundo Ibañez, C., & Dominguez, F. (2023). Minimally active neutralization of acid mine drainage through the Monte Carlo method. *Water*, 15(19), 3496. https://doi.org/10.3390/w15193496

Dakos, Z., Kupka, D., Kovařík, M., Jablonovská, K., Krištůfek, V., & Achimovičová, M. (2012). Secondary iron minerals present in AMD sediments from Smolník abandoned mine. *Nova Biotechnologica et Chimica*, 11(2), 87–92. https://doi.org/10.2478/v10296-012-0009-9

Demčák, S., Balintová, M., & Holub, M. (2020). Monitoring of the abandoned mine Smolnik (Slovakia) influence on the aquatic environment. *IOP Conference Series: Earth and Environmental Science*, 444(1), 012010. https://doi.org/10.1088/1755-1315/444/1/012010

Gaćina, R., & Dimitrijević, B. (2022). Reducing environmental impact caused by mining activities in limestone mines. *Podzemni radovi*, 40, 37–44. https://doi.org/10.5937/podrad2240037g

Guillon, S., Girard, J.-F., Williard, E., Virlogeux, D., & Descostes, M. (2024). Modeling subsurface contaminant transport from a former open-pit uranium mine in fractured granites (La Ribière, France): Reducing uncertainties with geophysics. *Journal of Contaminant Hydrology*, 263, 104343. https://doi.org/10.1016/j.jconhyd.2024.104343

Jamaluddin, Qulub, M. S., Manik, N., Umar, E. P., Ryka, H., & Putri, E. C. A. (2023). Lithological controls on acid mine drainage formation: An integrated rock characterization of AMD sources in the Seluang River area, East Kalimantan, Indonesia. *International Journal of Hydrological and Environmental for Sustainability*, 5(1), 22–37. https://doi.org/10.58524/ijhes.v5i1.1061

Kisková, J., Perháčová, Z., Vlčko, L., Sedláková, J., Kvasnová, S., & Pristaš, P. (2018). The bacterial population of neutral mine drainage water of Elizabeth's Shaft (Slovinky, Slovakia). *Current Microbiology*, 75(8), 988–996. https://doi.org/10.1007/s00284-018-1472-6

Lintnerová, O., Šottník, P., & Šoltés, S. (2008). Abandoned Smolník mine (Slovakia) – a catchment area affected by mining activities. *Estonian Journal of Earth Sciences*, 57(2), 104–110. https://doi.org/10.3176/earth.2008.2.06

Liu, H., Wu, Q., Chen, J., Wang, M., Zhao, D., & Duan, C. (2021). Environmental impacts related to closed mines in Inner Mongolia. *Sustainability*, 13(23), 13473. https://doi.org/10.3390/su132313473

Ly, T., Wright, J. R., Weit, N., McLimans, C. J., Ulrich, N., Tokarev, V., Valkanas, M. M., Trun, N., Rummel, S., & Grant, C. J. (2019). Microbial communities associated with passive acidic abandoned coal mine remediation. *Frontiers in Microbiology*, 10, 1955. https://doi.org/10.3389/fmicb.2019.01955

Matschullat, J., & Gutzmer, J. (2012). Mining and its environmental impacts. *In Encyclopedia of Sustainability Science and Technology* (pp. 6633–6645). Springer. https://doi.org/10.1007/978-1-4419-0851-3_205

Michaeli, E., Solar, V., Ivanova, M., Vilček, J., & Lisnyak, A. (2017). Environmental differences of land creation in time interval for determination of industrial influence on landscape. *Man and Environment. Issues of Neoecology*, 28(28), 114–119. https://doi.org/10.26565/1992-4224-2017-28-12

Murray, J., Kirschbaum, A., Dold, B., Mendes Guimarães, E., & Pannunzio Miner, E. (2014). Jarosite versus soluble iron-sulfate formation and their role in acid mine drainage formation at the Pan de Azúcar mine tailings (Zn-Pb-Ag), NW Argentina. *Minerals*, 4(2), 477–502. https://doi.org/10.3390/min4020477

Nancucheo, I., Bitencourt, J. A. P., Sahoo, P. K., Alves, J. O., Siqueira, J. O., & Oliveira, G. (2017). Recent developments in remediation of acid mine drainage using sulfate-reducing bacteria. *BioMed Research International*, 2017, 7256582. https://doi.org/10.1155/2017/7256582

Neculita, C. M., Zagury, G. J., & Bussière, B. (2007). Passive treatment of acid mine drainage in bioreactors using sulfate-reducing bacteria: Critical review and research needs. Journal of Environmental Quality, 36(1), 1–16. https://doi.org/10.2134/jeq2006.0067

Noor, I., Arifin, Y. F., Priatmadi, B. J., & Saidy, A. R. (2023). Laboratory simulation of the swampy forest system for the passive treatment of acid mine drainage in coal mine reclamation areas. Scientific Reports, 13(1), 1–10. https://doi.org/10.1038/s41598-023-32990-x

Oberholzer, M. M., Oberholster, P. J., Ndlela, L. L., Botha, A.-M., & Truter, J. C. (2022). Assessing alternative supporting organic materials for the enhancement of water reuse in subsurface constructed wetlands receiving acid mine drainage. *Recycling*, 7(3), 41. https://doi.org/10.3390/recycling7030041

Palihakkara, C. R., Dassanayake, S., Jayawardena, C., & Senanayake, I. P. (2018). Floating wetland treatment of acid mine drainage using Eichhornia crassipes (water hyacinth). *Journal of Health and Pollution*, 8(17), 14–19. https://doi.org/10.5696/2156-9614-8.17.14

Ruppen, D., Chituri, O. A., Meck, M. L., Pfenninger, N., & Wehrli, B. (2021). Community-based monitoring detects sources and risks of mining-related water pollution in Zimbabwe. *Frontiers in Environmental Science*, 9, 754540. https://doi.org/10.3389/fenvs.2021.754540

Rusko, M., Andráš, P., Kušnierová, M., Aschenbrenner, Š., Krnáč, J., & Dubiel, J. (2011). Formation of acid mine drainage water at Sb (Au) deposit Pezinok. *Research Papers Faculty of Materials Science and Technology Slovak University of Technology*, 19(31), 57–68. https://doi.org/10.2478/v10186-011-0056-0

Sienkiewicz, E., Gąsiorowski, M., Sekudewicz, I., Kowalewska, U., & Matoušková, Š. (2023). Responses of diatom composition and teratological forms to environmental pollution in a post-mining lake (SW Poland). *Environmental Science and Pollution Research*, 30(51), 110623–110638. https://doi.org/10.1007/s11356-023-30113-7

Šestinová, O., Findoráková, L., Hančuľák, J., Fedorová, E., & Špaldon, T. (2016). Terrestrial ecotoxicological tests as screening tool to assess soil contamination in Krompachy area. *IOP Conference Series: Earth and Environmental Science*, 44(5), 052041. https://doi.org/10.1088/1755-1315/44/5/052041

Šestinová, O., Hančuľák, J., & Findoráková, L. (2020). Environmental risk assessment of metal-contaminated areas using different bioassays. *Nova Biotechnologica et Chimica*, 19(2), 183–191. https://doi.org/10.36547/nbc.v19i2.654

Thiruvenkatachari, R., Younes, M., & Su, S. (2011). Coal mine site investigation of wastewater quality in Australia. *Desalination and Water Treatment*, 32(1–3), 357–364. https://doi.org/10.5004/dwt.2011.2722

Wibowo, Y. G., Fadhilah, R., Syarifuddin, H., Maryani, A. T., & Putri, I. A. (2021). A critical review of acid mine drainage treatment. Jurnal Presipitasi: Media Komunikasi dan Pengembangan Teknik Lingkungan, 18(3), 524–535. https://doi.org/10.14710/presipitasi.v18i3.524-535