Technologies for the Treatment of Mine Water

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Abstract *This paper presents an integrated analysis of both conventional and emerging technologies used in the treatment of contaminated waters resulting from mining operations, with a focus on chemical, biological, and advanced solutions such as nanomaterials and the ASEC system. The main purification mechanisms—such as neutralization, metal precipitation, phytoremediation, and the use of passive wetland systems—are highlighted, emphasizing the need to integrate them into a coherent management strategy. Case studies from China, Romania, and Western Europe validate the real-world applicability of these technologies. The results demonstrate that combining chemical and biological treatments within a circular economy model enhances efficiency, reduces environmental impact, and enables the recovery of valuable resources.*

Keywords: *acid mine drainage, ASEC technology, chemical neutralization, circular economy, nanomaterials, phytoremediation*

1 INTRODUCTION

Mining operations, particularly those targeting sulfide ore deposits, have over time generated one of the most persistent forms of environmental pollution: mine-impacted waters. These waters are characterized by extremely low pH, high concentrations of heavy metals (such as iron, copper, zinc, lead, cadmium, and arsenic), and significant levels of sulfate factors that severely degrade the quality of surface and groundwater, reduce soil fertility, disrupt aquatic ecosystem biodiversity, and indirectly threaten human health [1], [7].

The formation of acid mine drainage (AMD) is a complex process, resulting from the oxidation of metal sulfides—especially pyrite (FeS_2)—in the presence of oxygen and water, leading to the release of acids and metals in soluble forms [5]. This form of pollution can persist for decades or even centuries after mining operations cease, particularly in the absence of proper containment and treatment measures [6].

In Romania, as well as across Europe, the management of mine water remains a major challenge, given the diffuse nature of pollution sources, the lack of modern treatment infrastructure at many historical sites, and the cumulative impact of abandoned mining activities [7].

In this context, the existing legal framework—anchored in Directive 2000/60/EC of the European Parliament [3]—requires that all water bodies achieve good ecological status by 2027, which places increasing pressure on authorities and industrial operators to implement effective and sustainable remediation solutions.

Over the past two decades, international scientific research has made substantial progress in the field of mine water treatment technologies, proposing both traditional chemical methods—such as neutralization and coagulation-flocculation—as well as passive biological systems, including constructed wetlands and phytoremediation [1], [8]. In parallel, high-efficiency emerging technologies have been developed, such as the use of adsorptive nanomaterials [9], the application of advanced biotechnologies, and innovative sludge-free evaporation–crystallization techniques, such as the ASEC technology [2]. The process of acid mine drainage (AMD) formation is schematically illustrated in Figure 1, highlighting the key stages of metal sulfide oxidation and metal mobilization in acidic aqueous environments (Fig. 1).

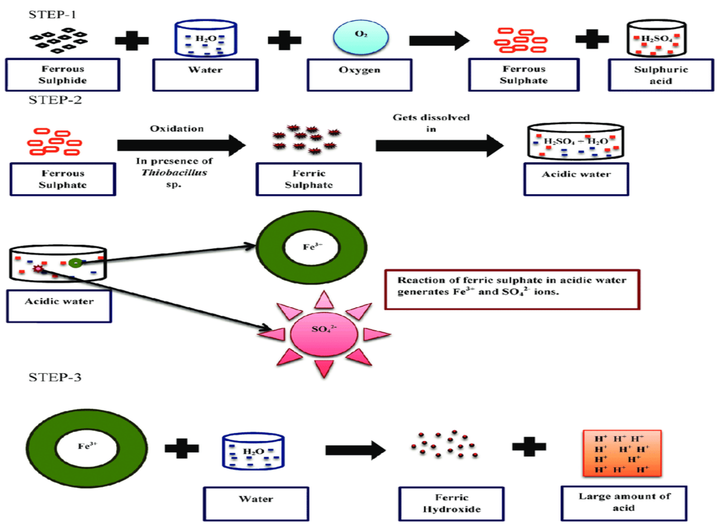

Fig. 1. Mechanism of formation of acid mine drainage [11].

Nevertheless, a significant gap persists in the integration of these technologies into a coherent management system. The absence of a unified platform that combines water quality diagnostics, adaptive selection of optimal treatment, real-time monitoring, and the valorization of metallic by-products has led to fragmented and often reactive interventions—lacking a strategic vision for resource recovery and pollution cycle closure [7], [10].

2 CHEMICAL PROCESSES FOR MINE WATER TREATMENT

The treatment of mine water through chemical methods remains one of the most widely applied and well-documented remediation strategies, successfully implemented in various mining regions across the globe. These processes aim to alter the chemical parameters of contaminated water in order to induce the precipitation of heavy metals and dissolved compounds, thereby facilitating their separation and removal [8].

The effectiveness of such technologies depends on several factors, including the water composition, initial pH, the types of metals present, and the specific operational conditions of each site [7].

2.1 Chemical neutralization

Neutralization is the first essential step in the treatment of acid mine drainage, with the primary goal of increasing the pH to an optimal range for the precipitation of dissolved metals.

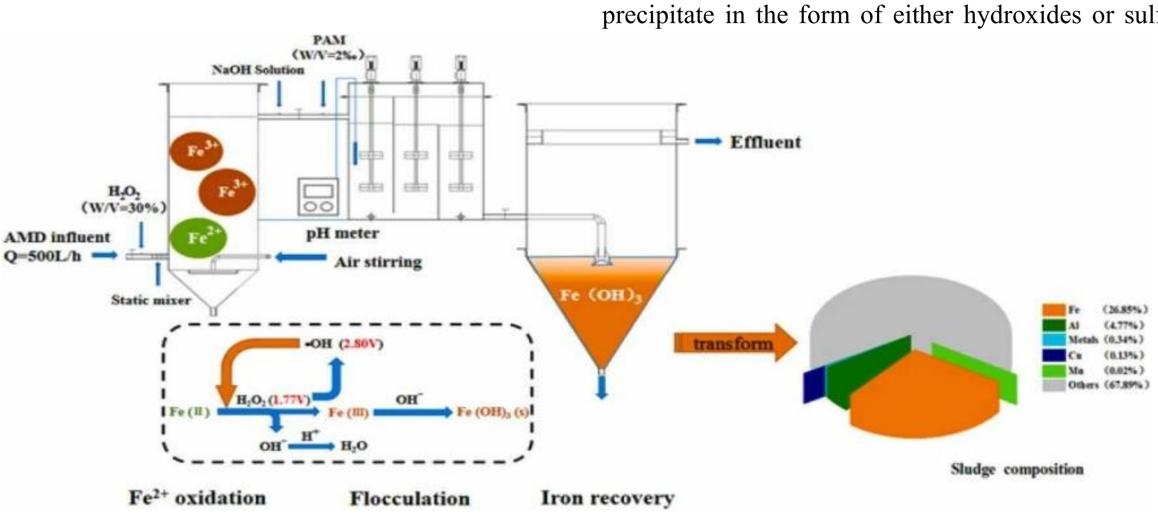

Fig. 2. Treatment and recovery of iron from acid mine drainage [12]

The process involves the addition of alkaline reagents that neutralize the acidity generated by the oxidation of metal sulfides—particularly pyrite (FeS_2) [6].

The most commonly used reagent is lime, either in the form of calcium oxide (CaO) or calcium hydroxide ($Ca(OH)_2$). The neutralization reactions are rapid and effective, leading to the formation of insoluble metal hydroxides and a significant reduction in water toxicity. A classic example is the precipitation reaction of iron:

$$Fe^{3+} + 3OH^{-} \rightarrow Fe(OH)^{3}\downarrow \qquad (1)$$

The formation of ferric hydroxide [$Fe(OH)_3$] precipitates in acid mine drainage is depicted in Figure X, illustrating the hydrolysis of Fe^{3+} ions under varying pH conditions (Fig. 2).

In addition to lime, the process commonly employs coagulant and flocculant reagents—such as ferric sulfate, aluminum chloride, or polyacrylamides—which promote the aggregation of particles and the formation of easily settleable flocs. This step is critical for improving solid–liquid separation efficiency and reducing the turbidity of the treated water.

Notable examples of the effectiveness of chemical neutralization can be observed at the Rio Tinto and Tharsis mining sites in Spain, where the application of lime treatment resulted in a reduction of Fe, Cu, and Zn concentrations by over 95%, while generating a stable sludge that is relatively easy to manage [2].

2.2 Precipitation and coagulation of heavy metals

After the initial neutralization, treatment must continue with the objective of fully removing the remaining heavy metals and sulfates from solution. This is achieved through chemical precipitation processes, followed by coagulation–flocculation and solid–liquid separation.

Metals such as zinc, copper, lead, and cadmium precipitate in the form of either hydroxides or sulfides, depending on the pH and the presence of other chemical agents. Sulfate precipitation can occur as gypsum ($CaSO_4 \cdot 2H_2O$), and in the presence of barium ions, it may result in the formation of barite ($BaSO_4$)—a highly stable compound with extremely low solubility [7].

The process of sulfate removal via ettringite precipitation is schematically depicted in Figure 3, highlighting the sequential steps involved in the treatment of mine water.

In this context, an innovative approach is represented by the ASEC technology—Adiabatic Sonic Evaporation and Crystallization—which introduces a fundamentally different method: the rapid adiabatic evaporation of contaminated water using sonic energy, followed by the controlled crystallization of dissolved salts and metals.

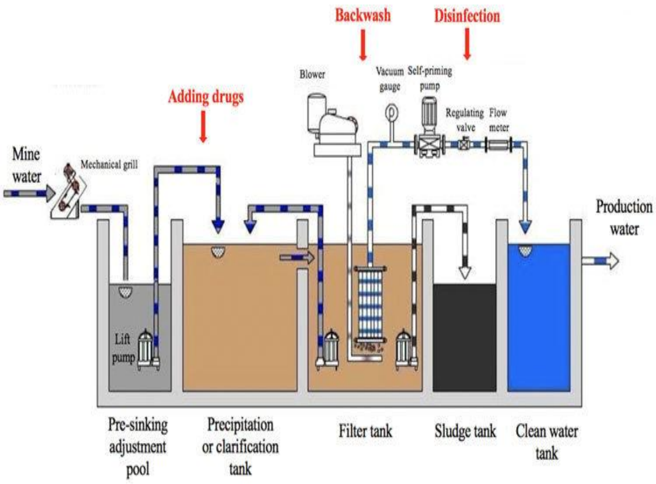

Fig. 3. The purification process of mine water [13]

This process enables the production of high-purity distilled water and valuable solid residues, without generating toxic sludge [2].

Unlike conventional methods, ASEC has the major advantage of integrating water purification with resource recovery, allowing for the complete separation of metals in dry form and eliminating the need for additional sludge treatment [2].

3 BIOLOGICAL PROCESSES FOR WATER TREATMENT

Biological treatment processes for contaminated waters originating from mining activities have gained increasing importance in the context of the global shift toward eco-friendly, sustainable, and low-impact environmental solutions. Unlike traditional chemical treatments, biological methods rely on living organisms—plants, bacteria, or complex microbial communities—to transform, immobilize, or extract pollutants from contaminated waters [1], [7].

These processes offer low operational costs, require minimal maintenance, and can be successfully integrated into long-term remediation strategies, particularly in abandoned or hard-to-access mining areas, where the installation and operation of advanced technologies may be impractical [1].

3.1 Phytoremediation of contaminated waters

Phytoremediation is a biological method that involves the use of plants capable of tolerating and extracting heavy metals from water or soil. These plants, known as hyperaccumulators, absorb toxic metals through their root systems and translocate them to aerial parts, where they can later be harvested and safely managed [1].

Species such as Phragmites australis (common reed), Typha latifolia (cattail), Salix spp. (willow), and Brassica juncea (Indian mustard) have been extensively studied for their capacity to accumulate metals such as copper, zinc, cadmium, and arsenic from mine-impacted waters [1]. Figure 4 illustrates the key mechanisms of phytoremediation in mining water treatment, including phytoextraction, phytostabilization, and rhizofiltration.

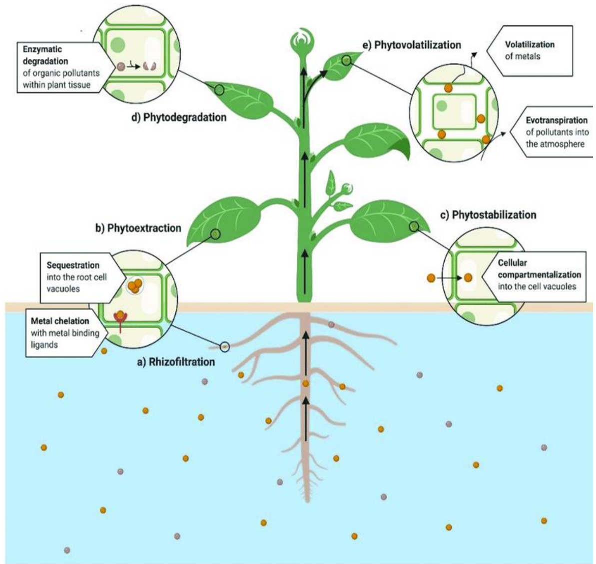

Fig. 4. General diagram of phytoremediation processes in water[14]

In addition to phytoextraction, other effective mechanisms included under phytoremediation are:

- Phytostabilization – a process by which plants limit the mobility of metals in the water column by immobilizing them within the rhizosphere;
- Rhizofiltration – the use of the plant's root system as a biological filtration medium, reducing pollutant loads through absorption and adsorption [1].

This method is ideal for passive treatment in wetlands, drainage channels, or settling ponds, offering a dual benefit: the reduction of pollution and the ecological rehabilitation of degraded landscapes [1], [8].

3.2 Passive treatment systems (constructed wetlands)

Constructed wetlands are a form of passive treatment technology that replicates, under controlled conditions, the natural functioning of wetland ecosystems. These systems consist of layered filtering materials (such as gravel, sand, and peat), planted with adaptive vegetation and colonized by microbial communities capable of degrading or immobilizing pollutants present in the water [8].

In the case of mine-impacted waters, the efficiency of these systems is largely ensured by the activity of sulfate-reducing bacteria (SRB). These microorganisms convert sulfate ions (SO_4^{2-}) into hydrogen sulfide (H_2S), which subsequently reacts with dissolved metals to form insoluble metal sulfides that settle into the filter bed:

Constructed wetlands can be classified into two main types:

- Horizontal flow systems – where water flows horizontally beneath the vegetative layer,
- Vertical flow systems – where water is introduced from the top and percolates downward through the substrate layers.

This reaction plays a significant role in reducing concentrations of heavy metals, particularly iron (Fe), copper (Cu), zinc (Zn), and cadmium (Cd) from the water column [5], [8], he process of acid mine drainage formation is schematically illustrated in Figure 5, highlighting the key stages of metal sulfide oxidation and metal mobilization in acidic aquatic environments. These systems have been successfully implemented at abandoned mining sites across Europe and North America, particularly for the treatment of acid mine drainage (AMD). They offer a sustainable alternative with low operational costs and proven long-term efficiency [8], [5].

Among these technologies, two stand out in particular:

- ASEC technology (Adiabatic Sonic Evaporation

$$M^{2+}+H_2S \rightarrow MS\downarrow+2H^+ \qquad (2)$$

and Crystallization), which allows for the complete separation of contaminants in crystalline form and the production of high-purity water, without generating residual sludge [2];

- Nano-structured adsorbents, developed using metal oxides, oxidized graphene, or functionalized activated carbon, which enable the efficient and selective capture of dissolved metals—even at very low concentrations [9].

4.1 ASEC Technology

ASEC technology (Adiabatic Sonic Evaporation and Crystallization) is a revolutionary solution developed for treating highly concentrated contaminated waters, including acid mine drainage with elevated levels of metals and sulfates [2].

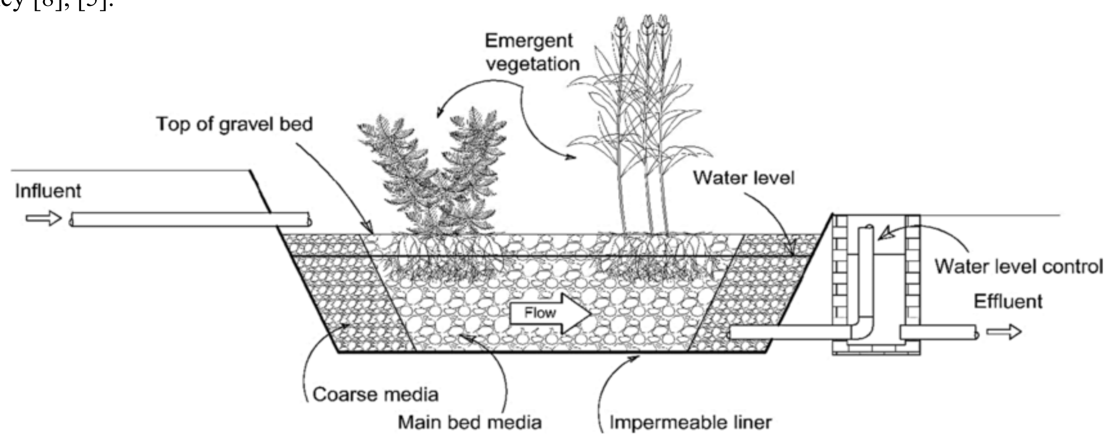

Fig. 5. Schematic of a horizontal subsurface flow constructed wetland [15]

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4. INNOVATIVE TECHNOLOGIES IN MINE WATER TREATMENT

Advancements over the past two decades in environmental science, chemical engineering, and nanotechnology have led to the development of innovative solutions for mine water treatment, offering significantly higher performance compared to traditional technologies [2], [9].

These emerging approaches aim not only to purify contaminated waters but also to integrate the principles of the circular economy—through the *recovery of valuable resources* such as heavy metals and by *reducing the environmental footprint* of treatment processes [2], [8].

The operating principle of ASEC is based on:

- accelerated adiabatic evaporation using high-intensity sound waves,
- condensation of the resulting vapor to obtain purified water,
- and controlled crystallization of salts and metals into solid form [2].

This process occurs without the use of chemical reagents and without generating residual sludge. Unlike conventional methods that separate metals through chemical precipitation, ASEC ensures the complete removal of contaminants, while producing two distinct output streams:

1. high-purity water, with conductivity below 56 µS/cm,
2. recoverable crystalline materials (iron, copper, zinc, sulfates) [2].

Experimental tests conducted at the Rio Tinto and Tharsis mining basins in Spain confirmed the 100% efficiency in metal removal and the potential for economic recovery of these materials. Additionally, ASEC technology features lower energy consumption compared to classical distillation or reverse osmosis systems and is completely free from toxic emissions or liquid residues [2].

The process of decontaminating dredged material and mining waters using Adiabatic Sonic Evaporation and Crystallization (ASEC) technology is schematically illustrated in Figure 6, highlighting the key stages of contaminant removal and resource recovery. This advanced treatment approach leverages adiabatic sonic energy to rapidly evaporate contaminated water under controlled thermodynamic conditions, thereby avoiding the need for chemical additives or high-pressure systems.

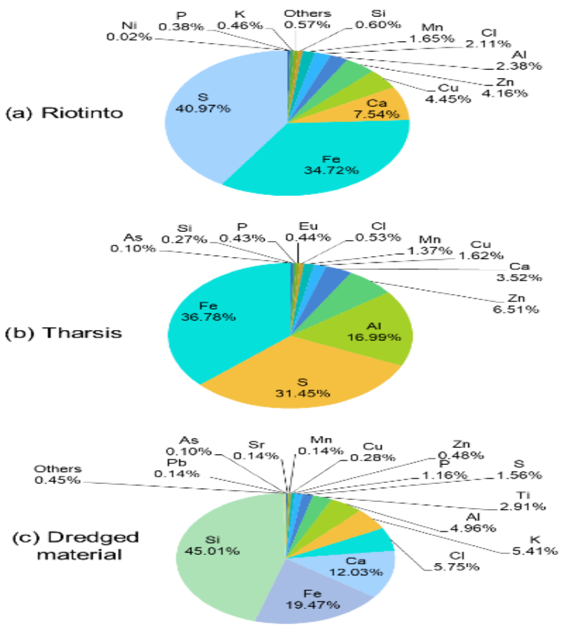

Fig. 6. Decontamination and Circular Economy of Dredged Material and Mining Waters Using (ASEC) Technology [2]

4.2 Advances in nanotechnology and advanced adsorbents

The use of nano-structured materials in mine water treatment represents another promising direction, enabling the efficient capture of heavy metals and other contaminants even at very low concentrations [9].
Nanomaterials such as metal oxide nanoparticles (Fe_2O_3, MnO_2), oxidized graphene, functionalized activated carbon, and modified zeolites possess extremely high specific surface areas and active functional groups that facilitate the selective adsorption of metal ions from acidic solutions [9]. The adsorption mechanism of heavy metals using carbon nanotubes (CNTs) is schematically illustrated in Figure 7, highlighting the key interactions between metal ions and the functionalized surfaces of CNTs. This diagram, adapted from Song et al. (2018), provides a visual representation of the processes involved in heavy metal adsorption by CNTs.

The major advantages of these materials include:

- high reaction rates,
- elevated adsorption capacity,
- and the ability to regenerate and reuse them across multiple cycles.

However, current limitations of this technology involve:

- high synthesis and functionalization costs of nanomaterials,
- chemical instability in highly acidic environments,
- and difficulties in post-treatment recovery without material loss [9].

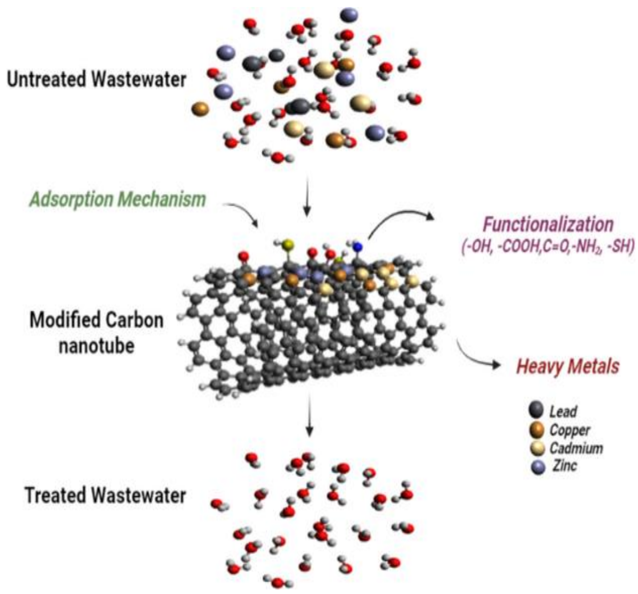

Fig. 7. Adsorption mechanism of heavy metals by using CNT [16]

Despite these challenges, future research directions are focusing on:

- the use of modified natural materials (e.g., clays, biochar, activated sludges),
- the integration of nanomaterials into hybrid filters or membranes with enhanced selectivity,
- and the development of smart adsorbents that can respond dynamically to pollutant concentration or environmental conditions [9].

5. RELEVANT CASE STUDIES

To assess the practical efficiency of various mine water treatment technologies, it is essential to analyze case studies applied in diverse geographical, geological, and economic contexts. This section presents three representative scenarios: an active mine in China with extremely high antimony content, a historically polluted mining area in Romania, and a series of phytoremediation applications across European sites affected by heavy metal contamination.

5.1 Remediation of Acidic Waters in China: The Xikuangshan Mine

The Xikuangshan Mine, located in Hunan Province, China, is the world's largest natural source of antimony (Sb) and a key site of concern regarding rare metal pollution. The mine waters generated in this area contain extremely high concentrations of antimony—exceeding 2.4 mg/L, which is more than 400 times the World Health Organization's permissible limit for drinking water [4].

The pollution results from the oxidation of stibnite (Sb_2S_3) and geochemical reactions between waste rocks and infiltrating water. To remediate this issue, the following technologies were implemented:

- chemical neutralization using lime and alkaline reagents;
- followed by advanced adsorption on modified natural materials.

In addition to reducing antimony concentrations below toxic thresholds, the implemented solutions enabled partial recovery of Sb for industrial reuse, thus providing a model of integrated intervention that combines treatment and resource valorization [4].

5.2 Mine Water Treatment in the Zlatna Region, Romania

The Zlatna region, located in the Apuseni Mountains of Romania, stands as an emblematic case of historical pollution caused by the extraction and processing of gold and polymetallic ores. The mine waters in this area are characterized by moderate acidity and high concentrations of iron, zinc, copper, and lead, which have negatively impacted local watercourses and the quality of groundwater [6].

Remediation projects in the area have included:

- conventional chemical treatments, based on neutralization and coagulation–flocculation;
- isotopic monitoring of water composition, using stable isotopes of oxygen and hydrogen to identify pollution sources and distinguish between different water types involved [6].

These methods made it possible to accurately trace pollution pathways and establish tailored intervention strategies for natural infiltrations versus mine gallery discharges. As a result, they led to a significant reduction in metal loadings in discharged waters and provided a solid scientific basis for local environmental decision-making [6].

5.3 Application of phytoremediation at the European level

Phytoremediation has been successfully applied across several mining sites in Western and Central Europe, particularly in areas impacted by the extraction of iron, lead, and zinc ores. Notable examples include:

- the former lead mine in Altenberg (Germany),
- the zinc quarries in Wallonia (Belgium),
- and mining sites in Wales (United Kingdom) [1].

The main objective was to stabilize contaminated sediments and reduce the metal load in surface waters using phytoextraction, phytostabilization, and rhizofiltration mechanisms [1].

Results showed an average reduction of 60 to 85% in heavy metal concentrations in water, depending on the plant species used, planting density, and substrate type [1].

Beyond technical efficiency, these projects have significantly contributed to:

- the ecological restoration of affected landscapes,
- the creation of new habitats for local fauna,
- and the increased public acceptance of passive remediation strategies [1].

6. CONCLUSIONS

The treatment of waters contaminated by mining activities remains one of the most complex and urgent environmental challenges—both in Romania and globally. Mine waters, especially those with acidic characteristics, contain high concentrations of heavy metals, sulfates, and other toxic substances, making it essential to apply efficient, flexible, and sustainable purification technologies over the long term [1], [6], [7].

The analysis of the technologies presented in this study leads to several key conclusions:

- Chemical processes, such as lime neutralization, coagulation, and metal precipitation, continue to serve as the cornerstone of primary treatment, offering high efficiency and fast action on soluble pollutants. However, these methods entail significant operational costs and generate sludges that require careful management [6], [7].
- Biological processes, including phytoremediation and constructed wetlands, provide an ecological and economical alternative for passive treatment—particularly in abandoned mining sites or regions with diffuse pollution. Their efficiency can be substantially enhanced when preceded by chemical stages [1], [8].
- Innovative technologies, such as ASEC and the use of nano-structured adsorbents, mark a paradigm shift by enabling complete water purification without sludge generation, while unlocking the potential for controlled and valuable recovery of metallic resources [2], [9].

A central takeaway from this study is the necessity of technological integration: no single process can offer a comprehensive solution for all types of mine water. Instead, combining chemical and biological stages, locally adapted and supported by advanced monitoring, can lead to maximum efficiency, cost control, and significant environmental impact reduction [2], [9].

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