MindMontan – Reduction of pollution in the Freiberger Mulde River in the Erzgebirge/Krušnohoří mining region through a passive water treatment plant

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Abstract

Many old, abandoned mines in Saxony discharge water contaminated with metals and metalloids into ground- and surface water. It is therefore foreseeable that the quality objectives of the European Water Framework Directive will not be achieved by 2027 without additional measures to reduce mining-related pollution. At the Hammerberg/Freiberg tailings pond, a cost-effective, modular passive treatment system has been successfully removing aluminium, cadmium and zinc from seepage water in several stages using combined microbial and chemical processes since July 2024. This system demonstrates that semi passive treatment can improve water quality with low energy, personnel and chemical consumption.

Keywords: Passive water treatment, tailings, acidic mine water, microbiology, sulfate reduction

Introduction

In the Ore Mountains mining region and adjacent areas, there are numerous abandoned mines and several thousand tailing heaps, of which the largest nearly 100 have a major influence on water pathways. Although large areas affected by uranium mining have already been remediated, the effect of historic mining on water systems persist for decades to centuries, for example through contamination with arsenic (As), cadmium (Cd), nickel (Ni), zinc (Zn), copper (Cu), uranium (U), and other potentially toxic elements. An efficient solution to this problem is challenging, as active technical treatment of mine water is economically feasible only at a few sites with high pollutant loads. Therefore, remediation efforts in Saxony have focused on major point sources of contaminated mine drainage, where active treatment is required to meet discharge limits.

Fig. 1 shows catchment areas of streams and rivers in Saxony that show increased levels of toxic metals and metalloids due to former ore and non-ferrous metal mining (Stevens *et al.* 2023). These discharges often cannot be treated and collectively place a substantial load on water bodies. It is foreseeable that approximately 16% of the 558 surface water bodies in Saxony will not achieve the quality objectives of the European Water Framework Directive (WFD) by 2027 without taking further steps.

The goal of passive water treatment methods is to enhance natural purification processes within a controlled treatment system, preventing pollutants from entering natural water bodies. In a review article, the pioneers of early passive mine water treatment systems (Kleinmann *et al.* 2021) describe these approaches as a cost-effective alternative to leaving many abandoned mine sites untreated. In Europe, such systems are far less widespread, although the United Kingdom plays a pioneering role (GOV UK 2016). Wolkersdorfer and Younger (2002) compiled passive treatment systems for mining-influenced waters known in Germany as of 2001.

The article presents the construction of an innovative passive treatment plant for seepage water from the Hammerberg tailings pond in Freiberg, combining both chemical and biological treatment stages. The construction of nature-based passive systems for the treatment of contaminated mine waters requires solid interdisciplinary expertise in geochemistry, hydrochemistry, microbiology, hydraulics, and botany. Site-specific pilot studies are therefore essential for successful project development.

Methods

The Hammerberg tailings pond located in Freiberg (Fig. 2) comprising industrial flotation residues was constructed in 1964 and operated until 1969. It contains approx. 330,000 m³ of fine-grained sludge with a thickness of 20–25 m, which was flushed into a small valley behind a dam built from coarse rock material. The main pollutants in the tailings are the elements As, lead (Pb), Cd, Cu and Zn. Underneath the tailings there is clay and weathered gneiss. At the deepest point of the pond a double-strand drainage pipe collects and drains the seepage water. Even more than 50 years after the tailings pond was closed, the seepage water still contains considerable contamination due to low pH values, high sulfate concentrations and contamination especially with the metals aluminium (Al), Cd and Zn (Tab. 1). It should be noted, that Cd is classified as a priority hazardous substance according to WFD (CAS number 7440-43-9). The remediation concept for the tailings pond includes a multi-layered cover to reduce the infiltration of rainwater and air as much as possible. However, even after covering, residual seepage is expected over a very long period. It must therefore be examined how it can be treated in order to protect the river Freiberger Mulde from the above-mentioned toxic metals in the long term.

The seepage water pilot treatment system has a modular design to separate the various pollutants in several treatment stages: First, the contaminated seepage water is pumped from the control shaft into small storage tanks (storage IBCs), from where it flows by gravity

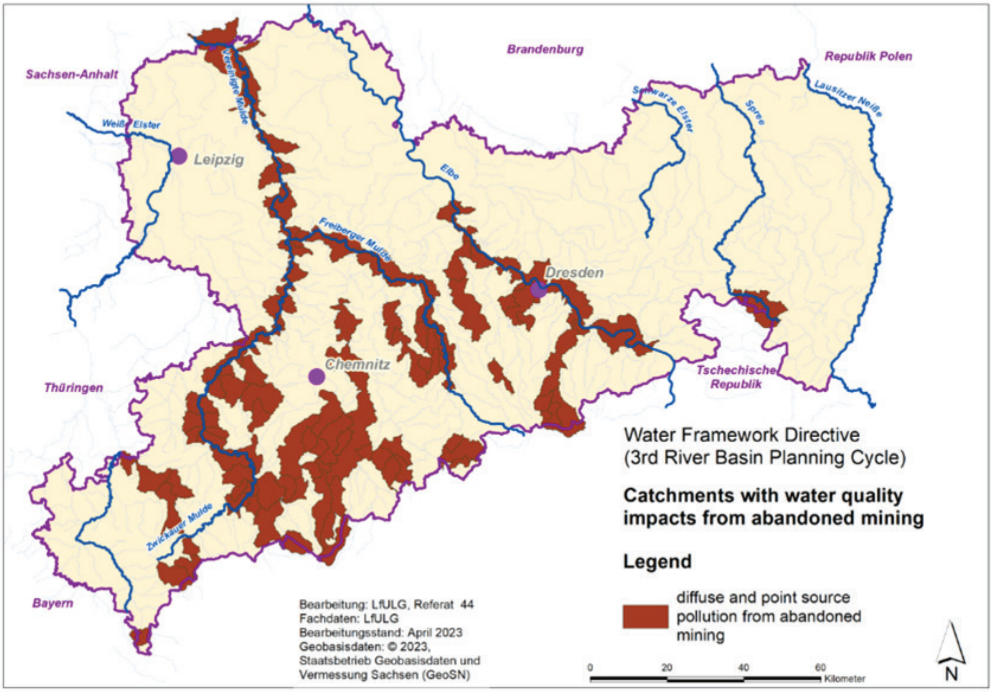

Figure 1 *Water quality influences from abandoned mines on surface water bodies in Saxony.*

Table 1 Minimum, maximum and average of selected parameters in the seepage water, shaft H, July 2024-November 2025 (without winter period November 2024-April 2025).

Element	Unit	Min	Max	Average
Aluminium	mg/L	1.01	173.0	14.8
Zinc	mg/L	11.9	62.1	33.7
Cadmium	mg/L	0.1	0.5	0.3
Sulfate	mg/L	1,000	2,087	1,578
pH	–	4.9	7.4	6.2
Redox potential (E_h)	mV	200	530	375
Oxygen content	mg/L	6.6	10.4	9.2

through the cascade-type treatment plant (Fig. 3). The electrical energy required for pumping is provided by a small photovoltaic (PV) system (sponsored by Meyer Burger Industries GmbH) with battery storage.

In the first treatment stage, the pH value of the acidic water is raised to between 6.5 and 7.0. In this pH range, the aluminium dissolved in the seepage water precipitates as $Al(OH)_3$ (Fig. 4). A special limestone (travertine Burgtonna, 93.7% $CaCO_3$) located in a filter column is used to raise the pH value. The $Al(OH)_3$ that accumulates in the travertine filter over time is flushed out with compressed air and water and collected in a filter bag (big bag).

The water then flows through a intermediate storage tank (clear water tank) into the vertically flow bioreactor (VFBR). The VFBR contains a mixture of limestone, wood chips, straw and compost, which is referred to as 'Biomix'. Sulfate-reducing bacteria grow in this mixture, producing hydrogen sulfide H_2S present as HS^- from the sulfate (SO_4^{2-}) in the

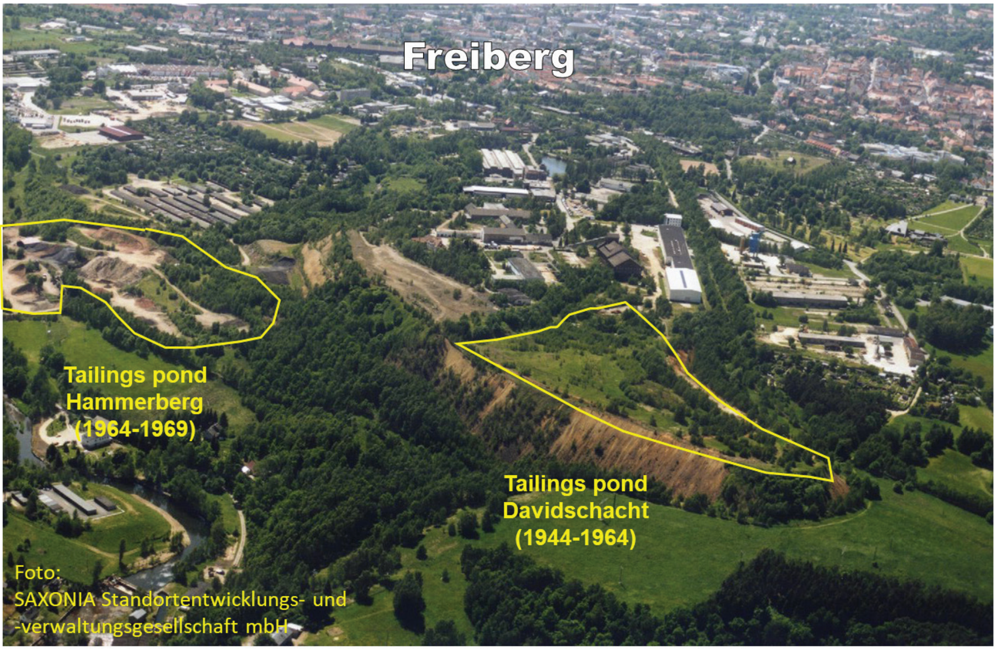

Figure 2 *View of the Davidschacht and Hammerberg tailings ponds at the eastern border of Freiberg.*

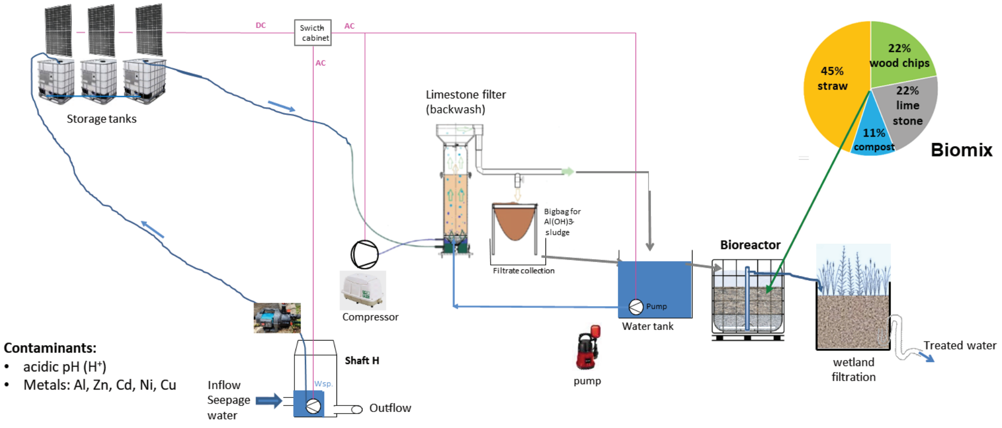

***Figure 3** Pilot plant layout at Hammerberg.*

leachate, which helps to precipitate the metals Zn, and Cd as metal sulfides (e.g. zinc sulfide ZnS) and retain them in the Biomix (Fig. 4).

All water samples collected were analysed both filtered and unfiltered in order to determine dissolved and particulate element concentrations.

As a final stage, the water to be treated must pass through a plant basin. Here, the water undergoes fine purification through filtration and the precipitation of any dissolved organic substances that may have been washed out of the VFBR.

Fig. 5 shows the structure of the complete pilot plant at Hammerberg. The plant is designed for a water throughput of 20–50 L/h and is being tested under various load conditions as part of the MindMontan project. The plant was commissioned in July 2024 and continuous operation was possible until the frost period at the beginning of November 2024. As the plant was not designed for winter operation for cost reasons, operation was suspended until spring 2025. In mid-April 2025, the plant was recommissioned for a new test period until winter 2025 and is scheduled to resume operation in April 2026.

Results

Fig. 6 shows the results of water treatment based on analyses of water quality at the several treatment stages. In the first treatment period in 2024, the contamination of the seepage water (shaft H) was higher than in the period from June 2025 onwards. This was particularly evident for aluminium, but also for other metals, with cadmium values shown as an example.

A reduction in the aluminium content of the seepage water can be obtained already in the storage basins. Two processes are responsible for this: (1) The degassing of dissolved carbon dioxide (CO_2), which leads to an increase in pH and thus to the partial precipitation of the dissolved Al^{3+}. (2) The settling of hydroxide sludge, which has either already been pumped up from the seepage water shaft or has subsequently precipitated in the storage basin due to the increase in pH value. The remaining dissolved Al

Neutralization:
$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$
Precipitation of of aluminiumhydroxide:
$Al^{3+} + 3OH^- \rightarrow Al(OH)_3\downarrow$

Sulfate reduction:
$SO_4^{2-} + 2CH_2O \rightarrow H^+ + HS^- + 2HCO_3^-$
Precipitation of metals (Cd, Zn):
$Cd^{2+} + HS^- \rightarrow CdS\downarrow + H^+$

***Figure 4** Simplified reactions in the limestone filter and in the VFBR.*

Figure 5 Pilot plant setup: PV modules and storage IBC (left), process stages: travertine filter, intermediate storage, vertical flow bioreactor (VFBR) and plant basin (right).

is precipitated in the travertine filter and retained there. However, there were a few test phases in which the filter discharged a higher Al content than originally present in the seepage water. This occurs because the travertine contains very fine-grained clay minerals, which are washed out during the filter's initial operation phase, temporarily increasing the Al concentration. The clay minerals are retained in the next stages, VFBR and plant basin (wetland).

Fig. 6 shows also the concentrations of Cd in the seepage water shaft and in the outflow of the individual treatment stages. The logarithmic plot was chosen to make the low Cd concentrations in the VFBR and wetland treatment stages more visible. In the first two stages (IBC storage tank and travertine filter), there is no change in the Cd concentration. The concentrations drop sharply only in the bioreactor, where the poorly soluble CdS precipitates. In the outflow of the VFBR, Cd concentrations below the limit of quantification were detected. This means that the Cd concentration is definitely less than 0.01 mg/L. By improving the limit of quantification, values <0.001 mg/L were even detected in the last tests (from July 2025). Due to increased throughput and unexpected intense rainfall, increased cadmium concentrations led to inhibition of the sulfate-reducing bacteria; consequently to reactivate the sulfate reducers, a one-off addition of sodium acetate as an additional carbon source was made on 22 August 2025 to support the system. It is noticeable that with the beginning of the winter period (from November), Cd separation in the VFBR becomes worse. This is related to the decreasing water temperature (< 5 °C), which

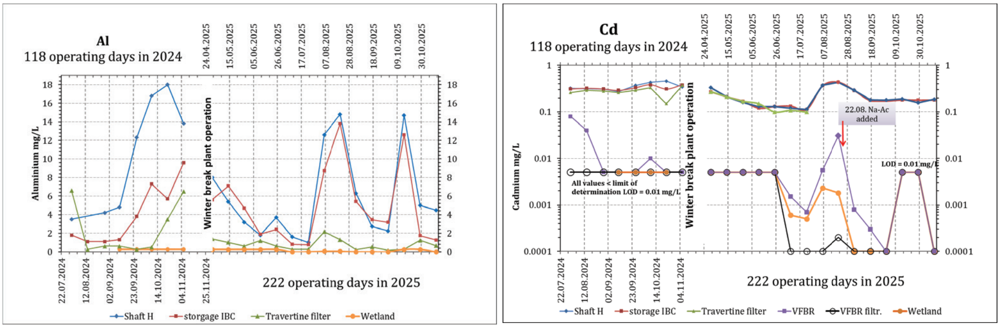

Figure 6 Al (left) and Cd (right) concentrations in the inflow water of the pilot plant (shaft H) and in the outflow of the various process stages.

leads to a slowdown in sulfate reduction and thus less HS^- is available for the formation of CdS. The hydraulic retention time (HRT) in the VFBR was estimated to vary within 17–50 hours (depending on the inflow).

Two approaches were used to evaluate the performance and efficiency of the process, treatment efficiency (TE) and volumetric metal removal rate (VMRR) (Tab. 2).

Compared to the zinc removal efficiencies published by Bailey *et al.* (2016) of up to a maximum of 11.2 g Zn/(m^3× d) in established bioreactor systems that use bacterial sulfate reduction, this system achieved an above-average efficiency rate of 21.3 g Zn/(m^3× d) in 2024 (Tab. 2).

In addition to the variables in the equations (Fig. 7), other independent parameters also have a relevant influence on the efficiency of the VFBR.

Conclusions and Outlook

The pilot plant concept was successfully validated, achieving high treatment efficiencies for Al, Zn and Cd. However, several parameters require more detailed investigation to understand their influence on the overall system. As the passive treatment system restarts in April 2026, additional data will be collected to support upscaling at the site assess transferability to other sites in Saxony. This includes determining the maximum hydraulic load capacity of the system, the treatment efficiency in the individual process stages, the temporal consumption of the Biomix and exploring option for its recycling. In addition, the general permitability and requirements beyond the research project must be clarified, as well as the expected operational expenditures (CapEx/OpEx).

Acknowledgements

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***Table 2** Treatment efficiency (TE, complete system) for Al, Zn, Cd and volumetric metal removal rate (VMRR, VFBR) for Zn in the passive pilot plant at Hammerberg.*

Element	Unit	2024	2025
TE			
Aluminium	%	97.6	97.8
Zinc	%	98.2	93.0
Cadmium	%	98.6	97.6
VMRR			
Zinc	g/m^3x d	21.3	20.8

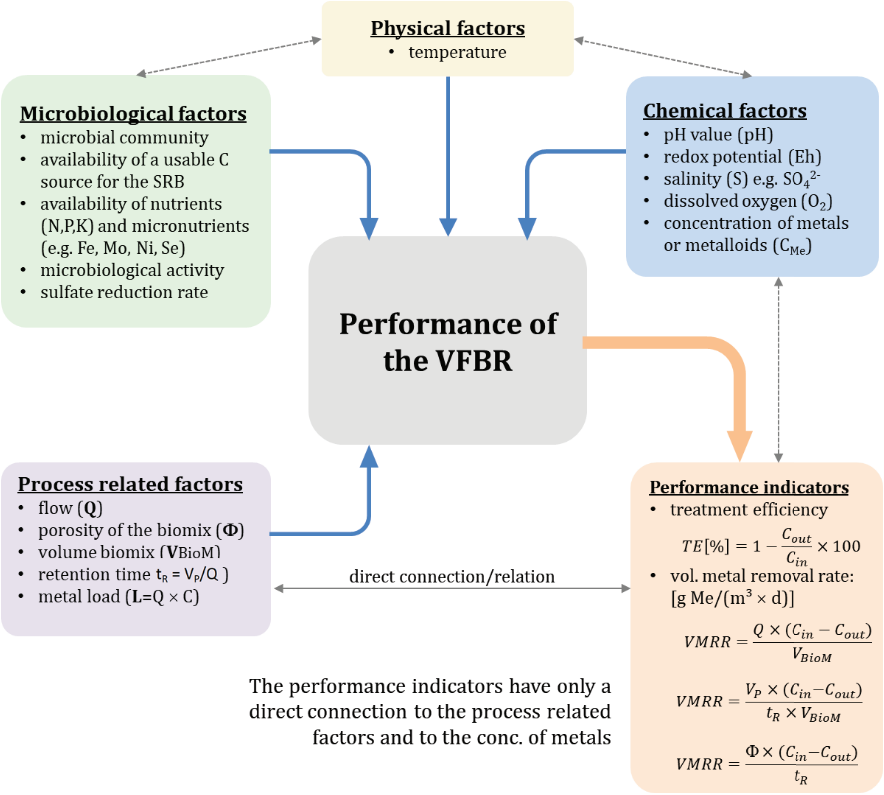

Figure 7 *Parameters affecting the performance of VFBR (Moghaddam 2025).*