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Biological iron removal and pigment recovery from acid mine drainage using native microbial consortia

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Abstract: The biological removal and recovery of iron from actual mine water were carried out using mining influenced water (MIW) sourced from the Smolník mine site in Slovakia. The oxidation of ferrous iron was improved by utilizing native acidophilic microbial communities, resulting in more than 99 % iron removal within 30 hours under acidic conditions. A stepwise treatment process – incorporating aeration, microbial oxidation, and controlled pH adjustment – facilitated the formation of iron precipitates, including schwertmannite and ferrihydrite. Elemental and structural analyses showed that these biologically formed precipitates contained low levels of arsenic, complying with regulatory standards for pigment applications. Overall, the findings demonstrate a sustainable approach that not only removes contaminants but also enables the recovery of valuable materials.

Key words: acid mine drainage, pigments, Smolník, bacterial oxidation, mining influenced water, schwertmannite

Introduction

Iron occurs widely as a contaminant in both natural source waters and industrial wastewaters (Nordstrom, 2011). In particular, mining and metallurgical activities generate substantial volumes of effluents characterized by elevated iron concentrations (Johnson & Hallberg, 2005). The presence of iron in aquatic systems poses huge risks to ecosystems and technical infrastructure, thereby efficient and sustainable removal technologies are needed for such purposes (Kaksonen & Janneck, 2024; Stumm & Morgan, 1996).

At the same time, iron represents a valuable resource with diverse industrial applications, highlighting the importance of its recovery rather than mere disposal. Among other uses, the resulting products – often natural or synthetic iron oxides – can subsequently serve as mineral pigments in a wide range of applications, including paints, stains, ceramics, plastics, and building materials.

Microbial processes offer promising solutions for both iron removal and resource recovery. Among these, iron-oxidizing microorganisms promote the formation and precipitation of iron minerals such as jarosite, schwertmannite, ferrihydrite, and goethite (Bigham et al., 1990).

In nature, iron occurs mainly in two oxidation states, as ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions. The prevailing form is dependent on pH, oxygen concentration, and redox conditions (Stumm & Morgan, 1996).

The oxidation of ferrous iron to ferric iron by dissolved oxygen is a complex and multi-step process. It involves the formation of transient, partially oxidized Fe^{2+}– Fe^{3+} intermediate phases, such as green rusts, which are metastable and challenging to characterize or predict. Over time, these intermediates undergo transformation into more thermodynamically stable iron oxide minerals, including hematite, magnetite, goethite, and lepidocrocite (Morgan & Lahav, 2007).

Mining influenced waters are commonly acidic due to the oxidation of sulfide minerals, such as pyrite, exposed during mining activities, which generates acidity and lowers the pH of the drainage waters (Johnson & Hallberg, 2005; Singer & Stumm, 1970; Wolkersdorfer, 2022).

In acidic environments, the abiotic oxidation of ferrous iron by dissolved oxygen is kinetically limited, as Fe^{2+} remains relatively stable at low pH (Morgan & Lahav, 2007). Consequently, spontaneous chemical oxidation proceeds slowly and is insufficient to account for the rapid iron cycling observed in acid mine drainage systems. Instead, this process is largely driven by the metabolic activity of acidophilic iron-oxidizing microorganisms, which catalyse the oxidation of ferrous to ferric iron at rates several orders of magnitude higher than abiotic reactions (Johnson et al., 2012).

The microbial oxidation of iron plays a central role in both natural and engineered systems, enabling efficient iron removal and influencing the formation of secondary iron

minerals. Biohydrometallurgical studies have demonstrated that near-complete ferrous iron oxidation can be achieved at pH values as low as 1.5 without the need for chemical neutralization, highlighting the advantages of biological processes over conventional chemical treatments (Kaksonen et al., 2014). These processes promote the formation of iron precipitates such as schwertmannite, jarosite, and goethite, which are critical for the removal of iron and associated contaminants from mine waters.

This study focuses on iron removal regarding acid mine drainage from the historical mining site in Smolník, Slovakia. In the recent years, pH of the mining influenced water from the main drainage shaft Pech, ranges from 3.95 to 4.12 and produces a high volume of mine water (approximately 6.5–10 L/s). Concentration of metals analysed in the water ranges according to the weather conditions and rainfall volumes (Tabs. 1 and 2).

Tab. 1
Change in the composition of mine water over the years (the month number is in parentheses), mg/L, n.a.: not analysed, partly published in Bártová (2025)

Shaft Pech	SO_4^{2-}	Fe	Al	Mn	Zn	Mg	Ca
2011	2,082	272	57.9	22.6	8.4	n. a.	n.a.
2020	1,722	232	40.3	16.5	4.4	n. a.	n.a.
2024 (12)	n. a.	223	44.8	17.6	5.5	192	69.5
2025 (4)	1,766	229	44.1	17.1	5.4	210	153
2025 (10)	n. a.	192	34.0	11.9	4	153	115
2026 (1)	2,138	260	48.5	14.7	5.16	308	104
2026 (2)	2,871	238	40.7	12.9	50.3	275	111

Tab. 2
Change in the composition of mine water over the years (the month number is in parentheses), µg/L, n.a.: not analysed, partly published in Bártová (2025)

Shaft Pech	Cu	Li	Co	Pb	As	Cd	Sb	Cr	Ni
2011	1,710	312	861	20.8	22	16.4	–	2.9	n. a.
2020	498	253	308	36.4	73	3.8	11.2	0.4	n. a.
2024 (12)	1,140	250	390	10.5	34.6	0.43	< 0.1	< 0.1	140
2025 (4)	1,070	290	410	12.1	28.4	0.85	< 0.1	< 0.1	n. a.
2025 (10)	400	190	210	41	35.7	2.4	0.15	1	130
2026 (1)	2,580	310	460	41.7	63.9	6.2	0.1	0.8	150
2026 (2)	1,750	n. a.	360	47.1	39.4	5.8	< 0.1	0.6	90

This study uniquely integrates microbial iron oxidation with controlled pH-driven precipitation to simultaneously achieve iron removal, selective metal retention, and production of value-added pigment materials from real mine water. The primary objective was to optimize Fe^{2+} oxidation and to characterize iron precipitates generated from an actual mine water under controlled laboratory conditions. Mine water samples were either inoculated with pre-cultivated iron-oxidizing acidophiles (native strains) or left uninoculated, enabling comparison between products formed via biological and abiotic oxidation.

Methods

Bacterial strains and incubation conditions

Native microbial consortia were cultivated for experimental purposes in mine water from the outflow of the main discharge shaft (Pech), supplemented with 9K salts to promote growth: 1.6 mmol/L $MgSO_4 \cdot 7H_2O$, 0.76 mmol/L $(NH_4)_2SO_4$, 0.23 mmol/L K_2HPO_4, and 120 mmol/L $FeSO_4 \cdot 7H_2O$. The cultures were maintained in baffled, magnetically stirred and aerated vessels (working volume 0.5 L) at 25 °C and 240 rpm in a temperature-controlled incubator. Microbial culture was subcultured 5 times before the final inoculation used in the experiment.

Mine water parameters

Tab. 3
Parameters of the Smolník mine water (2026), n.a.: not analysed

pH	ORP	Conductivity	Temperature	Flow rate
–	mV	mS/cm	°C	L/s
3.95	286.4	2.53	11.7	n. a.

pH/ ORP analysis

A combined glass electrode (InLab Micro Mettler Toledo) was used for pH measurement. The oxidation-reduction potential (ORP) of the liquid phase during bacterial iron oxidation was measured with a combined Pt-Ag/AgCl redox electrode (InLab Redox Micro Mettler Toledo). In both cases, the Seven2Go S2 (Mettler Toledo) was used.

Iron speciation

Ferric iron was determined with a UV-spectrophotometric method at 300 nm (Basaran & Tuovinen, 1986). Ferrous iron concentrations were determined by a modified o-phenanthroline spectrophotometric method, insensitive to Fe^{3+} interference (Herrera et al., 1989).

Cell monitoring

Presence of microbial cells was confirmed by direct microscopic count using a Neubauer counting chamber with a depth of 0.01 mm.

Chemical analyses

Elemental analysis of the water was done using AAS (Varian AA240Z, AA240FS) and ICP-MS 7700 (Agilent). Sulfate concentration was analysed by ion chromatography (Dionex ICS 5000). Total iron was determined using AAS.

The microstructure and morphology

Iron powders were investigated by MIRA 3 FE-SEM scanning electron microscope (TESCAN GROUP, a. s.) with an EDX detector (Oxford Instruments).

XRPD patterns were obtained using a D8 Advance diffractometer (Bruker) operating with Cu Kα radiation in the Bragg-Brentano configuration.

Elemental composition was determined using a hand-held X-ray fluorescence (XRF) analyzer (X-MET8000 Expert Geo, Hitachi High-Tech), equipped with a silicon drift detector (SDD) and an X-ray tube operating up to 50 kV.

Colour measurements

Colour measurements were performed using a Nix™ Spectro 2 Color Sensor with D50 2° settings. The sensor produces scan results in various colour systems (Stiglitz et al., 2016). For the purposes of this study, all data are expressed in the CIEL*a*b* colour space (Robertson, 1977).

Results and discussion

Water collected from the Smolník site was analysed and treated in order to remove dissolved iron and recover precipitates usable as mineral pigments in form of powders. Air-dried precipitates were then characterised using X-ray diffraction (XRD), X-ray fluorescence (XRF), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and NIX™ colour determination instruments. Liquid samples and resulting mine water after Fe-precipitates removal were analysed using atomic absorption spectroscopy (AAS).

Initial composition of the mine water is given in the Tab. 1 and Tab. 2 in the last row [2026(2)]. During the experiment, concentrations of Fe, As, Al, Mg, Mn, Cu, Co and SO^{2-}_4 were followed, as these elements either form a pigment structure (Fe, Al, S) or they are considered an unwanted impurity, often exhibiting toxic characteristics (As) or they are considered a valuable component of the water (Cu, Co, Mg, Mn) where leaving them in the water might lead to possibilities of their subsequent recovery from already iron-free solutions.

The formation of iron precipitates (pigments) in mine water was performed as a sequential process consisting of three main stages: (i) the initial aeration of MIW (30 hours) in order to lower pH and to oxidise and precipitate a small amount of Fe to remove a phase on which arsenic can be sorbed and which can be removed from the solution, (ii) the subsequent bacterial inoculation to accelerate ferrous iron oxidation, and (iii) pH adjustment in order to precipitate poorly crystalline iron phases such as ferrihydrite or schwertmannite. Subsequently, the gradual transformation of these metastable phases into more thermodynamically stable minerals, including goethite or hematite, can be achieved over time. Between individual stages, Fe-precipitates were filtered out from the solution using a PES filter with a pore size of 0.20 μm.

Iron oxidation

Enhanced ferrous iron oxidation is minor or negligible at pH below 4 (Jones et al., 2014; Morgan & Lahav, 2007). As the pH of Smolník MIW already oscillates around this value, and after several hours of aeration the value drops below 3.5, in order to accelerate iron oxidation, acidophilic microbial consortia need to be introduced into the process. Despite the genotypic differences, many acidophilic iron oxidisers share many common physiological traits (Kupka et al., 2023). For this reason, native microbial species were preferred over pure collection species, which can be costly and their purity needs to be confirmed over a longer period of time to ensure, that we are still working with the declared species. Native microbial consortia isolated directly from Smolník MIW were pre-cultivated and subsequently used for the process of iron oxidation.

2L of Smolník MIW was aerated for 30 hours and then filtrated to collect the first iron phase (A). The filtered water was transferred into a new flask (working volume 5 L), and 50 mL of an exponentially growing microbial culture (approximately 2.0×10^6 cells/mL) was added. Iron introduced with the growth medium was not taken into account.

Iron oxidation processes were monitored over an additional 30 hours, where already within first 21 hours the ferrous iron concentration dropped substantially. After 29 hours the Fe^{2+} concentration decreased below 2 mg/L (Fig. 1), corresponding to a removal efficiency exceeding 99 % (Fig. 2).

After iron oxidation was completed, the water was again filtered and iron precipitates were collected for the latter analyses (B).

After the filtration step, the water was divided into three flasks for the final step of the pH adjustment. The starting point for each of the adjustment was pH 2.6. From this point the pH was increased to values (i) 3.2 (optimal stability level to form schwertmannite), (ii) 4.1 (current

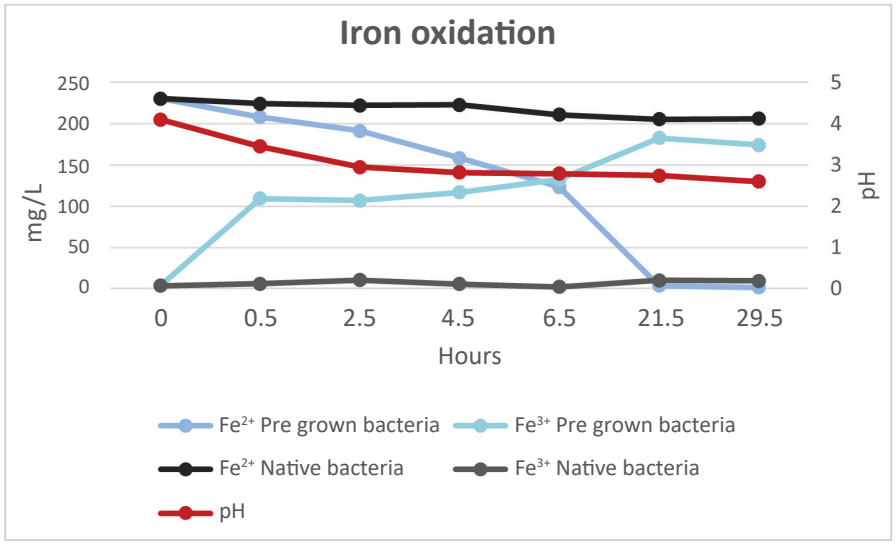


Fig. 1. Iron oxidation monitored via Fe^{2+} and Fe^{3+} concentration change over 30 h

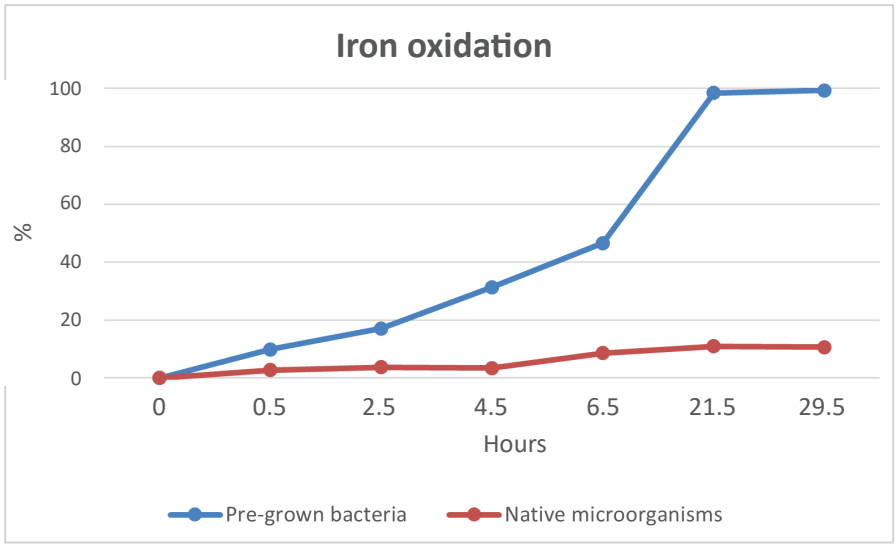


Fig. 2. Efficiency of Fe^{2+} removal/ oxidation exceeding 99 %

Smolník MIW pH), (iii) 5.5 (high efficiency level for Al precipitation), and (iv) 6.2 (fast ferrihydrite formation + complete Al removal), using 20 % NaOH. After each adjustment step the precipitate was filtered out and the water either continued for another round of treatment or it was stabilised using concentrated HNO_3 and subsequently analysed using AAS (Tab. 4). It should be noted that, the pH of 5.5 was obtained by using the filtrate from water previously adjusted to pH 3.2, as a substantial iron concentration remained in this sample.

As table 4 shows, the majority of Fe was effectively removed during bacterial oxidation, without any further pH adjustments. Applying pH levels above 4.1, the Fe concentration complied with the Regulation No. 269/2010 Coll., for total iron in discharged wastewater, which is 2 mg/L. Aluminium was effectively removed from the solution at pH 5.5, as it was expected. Co, Cu, Mg, and Mn did not co-precipitate from the water at pH below 4.1

Tab. 4
Final elemental composition of mine water after the pH adjustment and precipitates removal

Name	Conditions	Fe [mg/L]	Al [mg/L]	Mn [mg/L]	Mg [mg/L]	Cu [µg/L]	As [µg/L]	Co [µg/L]
–	initial MIW	238.8	40.7	12.88	275.3	1750	39.4	359.9
A	30 hours aeration	196.5	40.9	13.12	277	1740	15.7	369.4
B	bacterial oxidation	15.68	42.2	13.22	273.1	1780	3.3	368.3
C	pH 3.2	8.39	38.8	13.18	246.3	1750	2.3	404.2
D	pH 4.1	0.21	32.7	13.03	236	1610	1.9	394.1
E	pH 5.5	0.05	0	11.7	216.3	210	1.8	400.2
F	pH 6.2	0.05	0	10.99	210.9	60	1.8	334.6

and such water may be used for their subsequent recovery. Most arsenic was removed during the initial aeration step. In the second step of the bacterial oxidation, the remaining arsenic concentration also complied with the Regulation No. 269/2010 Coll., for arsenic in discharged wastewater, which is 0.02 mg/L.

Pigments from the first two steps (i, ii) of the formation of iron precipitates were analysed using handheld X-ray fluorescence (XRF) analyser to confirm their elemental composition and to ensure that resulting products do not contain high concentrations of arsenic (or other potentially toxic elements). XRF analysis showed that product A (30-hour aeration) contained high concentrations of arsenic (384 mg/kg). In product B (bacterial oxidation) only minor arsenic traces were detected, 20 mg/kg. This value already complies with the European Commission criteria which claims, that pigments used shall not be based on Cd, Pb, Cr^{6+}, Hg, As, Se, Sb or Co, where the following impurities from any pigments used shall not be present in the final product formulation in quantities exceeding 100 mg/kg (Commission Decission 2025/2607). According to this definition, sample B could already be considered a usable product as a pigment. Remaining iron oxides resulting from the pH adjustment were not examined by XRF method since according to Tab. 2. As was not detected in the source water at sufficiently high concentration.

All samples were characterised using XRD. The obtained patterns of the iron precipitates show mostly broad and low-intensity reflections, indicating that all solids are poorly crystalline. Considering the low pH and high sulfate concentrations of the mine water, samples formed at pH < 4.1 are most consistent with schwertmannite-type Fe(III), oxyhydroxysulfate precipitates. At higher pH (5.5–6.2), the precipitates likely shift toward poorly crystalline ferrihydrite-like Fe oxyhydroxides. No sharp reflections characteristic of well-crystallized hematite or goethite are observed, indicating that the solids are freshly formed and structurally disordered (Fig. 3).

Elemental composition of precipitates was analysed by scanning electron microscopy (SEM) coupled with energy-dispersive X-ray (EDX) detection (Tab. 5).

EDS analysis revealed a transition from Fe-rich oxyhydroxysulfate phases (schwertmannite-like) at low pH (Fig.4) to Al-rich hydroxide phases at higher pH (Fig. 5), confirming a sequential precipitation mechanism controlled by microbial oxidation and pH adjustment.

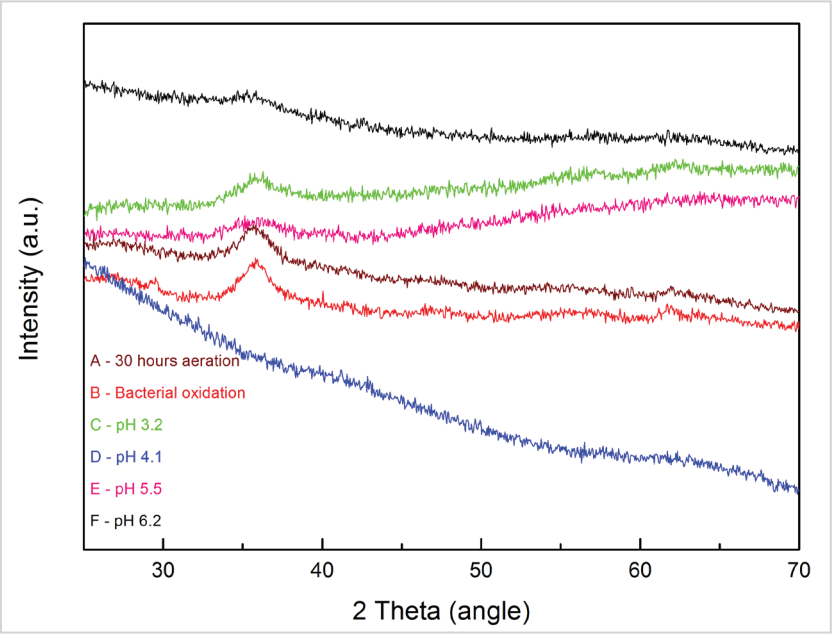


Fig. 3. XRD patterns of precipitates: A, B – without pH adjustment; C, D, E, F – with pH adjustment

Tab. 5
Elemental composition of precipitates according to SEM-EDS analyses (all values are expressed in At %)

Name	Conditions	O	Fe	S	Al	Si	K	Cu	Co	Mg	Mn	Zn	As
–	**30 hours aeration**	75.4	18.9	3.8	1.4	–	–	0.2	0.2	0.1	0.0	–	0.0
A	**Bacterial oxidation**	70.8	23.8	5.0	–	–	–	0.3	0.1	0.0	0.0	–	0.0
B	**pH 3.2**	68.2	20.6	5.2	5.2	–	0.3	0.2	0.1	0.1	0.1	–	0.0
C	**pH 4.1**	69.8	21.5	5.4	2.3	–	0.3	0.1	0.1	0.2	0.2	–	0.0
D	**pH 5.5**	70.0	2.9	3.6	19.0	3.1	0.2	0.6	0.0	0.0	0.3	0.3	0.0
E	**pH 6.2**	72.1	13.9	2.8	8.0	2.2	0.6	0.2	0.0	0.1	0.0	–	0.0

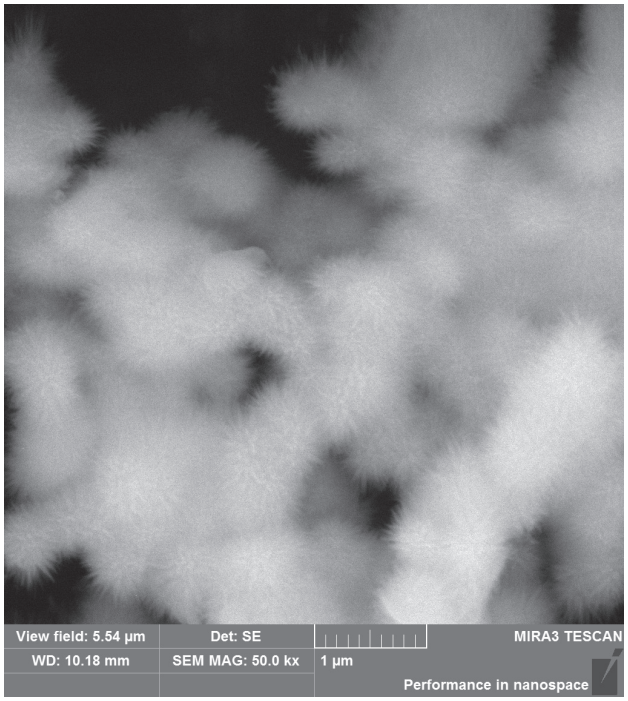


Fig. 4. Morphology of the surface of Fe-rich oxyhydroxysulfate phases (schwertmannite-like) at low pH 2.6 after bacterial iron oxidation

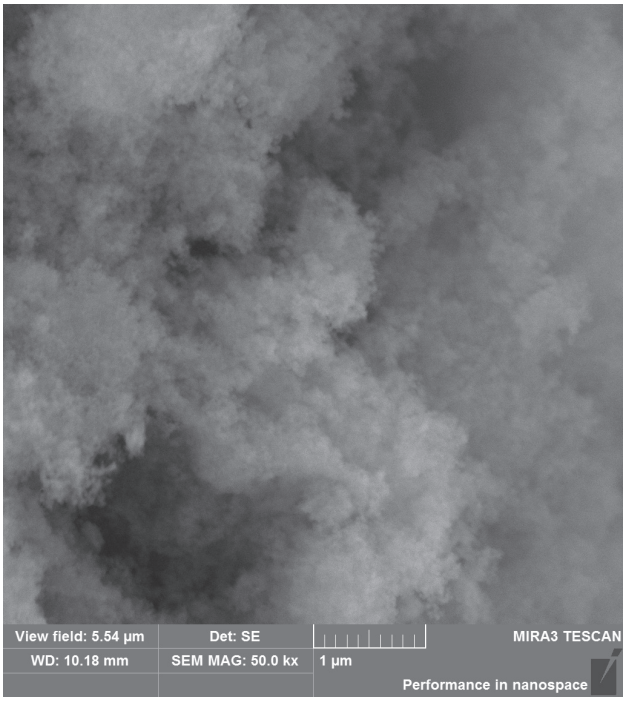
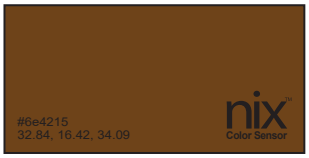
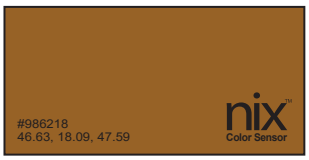
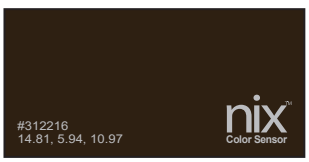
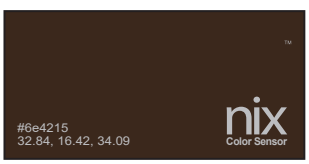


Fig. 5. Morphology of poorly crystalline ferrihydrite-like Fe oxyhydroxides following adjustment to pH 6.2

Tab. 6
Precipitates characterisation according to XRD and SEM-EDS analyses

Name	Conditions	Description
A	**30 hours aeration**	Predominantly amorphous to poorly crystalline Fe-rich sulfate-bearing oxyhydroxide, likely ferrihydrite- to schwertmannite-like, with minor Al-silicate traces.
B	**Bacterial oxidation**	Amorphous to poorly crystalline Fe-rich oxyhydroxide with significant sulfate association (schwertmannite-like) and minor trace metals.
C	**pH 3.2**	Mixed Fe-Al oxyhydroxide phase with minor sulfate and trace metal components; poorly crystalline.
D	**pH 4.1**	Fe-rich oxyhydroxide with notable sulfate association (possibly schwertmannite-like) and minor Al and trace metals; low crystallinity.
E	**pH 5.5**	Al-rich hydroxide/hydroxysulfate phase (basaluminite- or hydrobasaluminite-like) with minor Fe oxyhydroxide and silicates.
F	**pH 6.2**	Al-rich hydroxide/hydroxysulfate phase (basaluminite- or hydrobasaluminite-like) with minor Fe oxyhydroxide and silicate components.

Tab. 7
Colour characterisation of prepared precipitates/pigments

→		CIE L*a*b*	Nix Color
A	**30 hours aeration**	CIELAB: 32.84, 16.42, 34.09	
B	**bacterial oxidation**	CIELAB: 46.63, 18.09, 47.59	
C	**pH 3.2**	CIELAB: 34.16, 14.59, 26.14	
D	**pH 4.1**	CIELAB: 14.81, 5.94, 10.97	
E	**pH 5.5**	CIELAB: 48.80, 8.82, 26.42	
F	**pH 6.2**	CIELAB: 18.80, 6.78, 11.48	

Mineralogical and compositional characteristics of the precipitates obtained under different experimental conditions determined by XRD and SEM-EDS analyses reflect the progressive removal of iron and the increasing influence of aluminium precipitation as pH increases. The presence of sulfate and minor trace elements across several samples suggests their incorporation into poorly crystalline phases, such as ferrihydrite- or schwertmannite-like materials at acidic conditions, and basaluminite-type phases at near-neutral pH. Overall, the observed mineral transformations highlight the strong dependence of precipitate composition and structure on pH and oxidation conditions (Tab. 6).

The colour of iron precipitates is a critical parameter for their potential application as pigments, as it directly influences both their aesthetic appeal and commercial value. Colour variations are strongly governed by mineral phase, degree of crystallinity, particle size, and chemical composition, all of which affect optical properties such as light absorption and scattering (Cornell & Schwertmann, 2003). In addition, impurities and substitutions (e.g., Al, sulfate, or trace metals) can modify hue and stability, affecting pigment performance (Bigham et al., 1990; Schwertmann & Cornell, 2000). To quantitatively evaluate these properties, it is convenient to express colour values in the CIE L*a*b* colour space system, which provides a standardized, device-independent framework based on lightness (L*) and chromatic coordinates (a*, b*). This system correlates well with human visual perception and enables precise comparison between samples, including

the calculation of colour differences (ΔE), making it particularly suitable for pigment characterization and quality control (Mclaren, 1976; Robertson, 1977).

To determine colour, Nix™ Spectro 2 Color Sensor was used. The Nix Pro Color Sensor is able to determine the true colour of a soil sample regardless of moisture content, which is based on positive correlations between Nix Pro Color Sensor scans for samples in dry and moist conditions (Stiglitz et al., 2016).

The synthesized iron precipitates exhibited a wide range of colour coordinates in the CIE L*a*b* space (L* = 14.81–48.80, a* = 5.94–18.09, b* = 10.97–47.59), corresponding to dark brown, brown, and yellow- to orange-brown (ochre-like) hues typical of iron-based pigments (Tab. 7). The consistently positive a* and b* values indicate the predominance of red and yellow chromatic components, while variations in L* reflect differences in lightness among the samples. These colour differences can be related to the identified mineral phases and compositions, where Fe-rich oxyhydroxides (ferrihydrite- to schwertmannite-like) tend to produce darker brown to orange-brown hues, while Al-rich hydroxide/hydroxysulfate phases are associated with lighter, more yellowish tones (Cornell & Schwertmann, 2003; Schwertmann & Cornell, 2000). In addition, sulfate incorporation and the presence of trace elements can influence colour intensity and saturation, particularly in poorly crystalline Fe-phases such as schwertmannite (Bigham et al., 1990). From an application perspective, this variability is advantageous, as it enables the production of a range of earth-tone pigments from a single secondary raw material. Such pigments are suitable for use in construction materials, coatings, ceramics, and decorative applications. Overall, these findings demonstrate that mine water can serve not only as a source of iron-rich precipitates but also as a promising feedstock for the sustainable production of inorganic pigments with tunable colour properties.

Conclusions

Despite extensive research on acid mine drainage (AMD) treatment, most studies have focused on iron removal, microbial oxidation, or mineral formation separately. The integration of biological oxidation with controlled precipitation for simultaneous contaminant removal and resource recovery remains limited, particularly in real AMD systems. In addition, the role and performance of native microbial consortia under field-relevant conditions have not been adequately addressed.

This study demonstrates that coupling microbial Fe^{2+} oxidation with staged pH adjustment enables efficient iron removal from authentic mine water while generating iron-rich precipitates with properties suitable for pigment applications. Native acidophilic microorganisms showed high activity under acidic conditions, eliminating the need for intensive chemical inputs and highlighting their practical applicability.

Importantly, the process allows selective iron removal while retaining dissolved metals such as Cu, Co, Mn, and Mg in solution, creating opportunities for their downstream recovery. These metals could be recovered in subsequent treatment steps, such as selective precipitation, adsorption, or solvent extraction, depending on their chemical speciation. The combined treatment and valorization approach enhances both environmental and economic performance.

Overall, this work presents an integrated and sustainable strategy that advances AMD treatment beyond remediation toward resource recovery, supporting the development of circular and value-driven water management solutions. The results are directly applicable to the treatment of mining-influenced waters at the Smolník site and similar AMD-affected localities.

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Biologické odstránenie železa a súčasné získavanie pigmentov z kyslých banských vôd s využitím prirodzene sa vyskytujúcich mikrobiálnych spoločenstiev

Táto práca sa zaoberá biologickým odstraňovaním a súčasným získavaním železa z reálnej banskej vody (*mining influenced water*, MIW) z lokality Smolník. Vzhľadom na vysokú koncentráciu železa a prítomnosť sprievodných prvkov predstavuje takáto voda environmentálny problém, ale zároveň potenciálny zdroj sekundárnych surovín. Cieľom práce bolo optimalizovať proces oxidácie Fe^{2+} pomocou natívnych acidofilných mikroorganizmov a charakterizovať vzniknuté zrazeniny z hľadiska ich potenciálneho využitia ako minerálnych pigmentov.

Proces odstránenia železa a jeho následné získavanie vo forme pigmentov pozostával z troch hlavných krokov: (i) počiatočnej aerácie banskej vody, (ii) biologickej oxidácie železa pomocou natívnych mikrobiálnych konzorcií izolovaných priamo z lokality Smolník a (iii) postupnej úpravy pH s cieľom tvorby pevných fáz. Výsledky ukázali, že biologická oxidácia Fe^{2+} výrazne urýchľuje proces oxidácie železa aj pri nízkych hodnotách pH, pričom účinnosť odstránenia železa presiahla 99 % v priebehu 30 hodín.

Mineralogická charakterizácia (XRD) a chemická analýza (SEM-EDS, XRF) preukázali, že pri nižších hodnotách pH vznikajú prevažne slabo kryštalické Fe-oxyhydroxysulfátové fázy typu schwertmannit, zatiaľ čo pri vyšších hodnotách pH sa tvorí ferrihydrit a hydroxidové fázy bohaté na Al. Výsledky potvrdzujú, že zloženie a štruktúra precipitátov sú silne závislé od pH a oxidačných podmienok.

Z hľadiska chemického zloženia sa preukázalo, že väčšina železa je odstránená už počas biologickej oxidácie, zatiaľ čo ďalšie prvky ako Cu, Co, Mn a Mg zostávajú v roztoku. To vytvára predpoklady na ich následné získanie. Arzén bol účinne odstránený už v počiatočnej fáze aerácie a jeho koncentrácia v produktoch spĺňala legislatívne limity na využitie pigmentov.

Farebná charakterizácia (CIELab*) ukázala, že pripravené materiály vykazujú široké spektrum odtieňov od tmavohnedej po žltooranžovú, typických pre železité pigmenty. Tieto vlastnosti spolu s ich chemickým zložením naznačujú možnosť ich využitia v stavebných materiáloch, farbách alebo keramike.

Výsledky práce ukazujú, že kombinácia biologickej oxidácie železa a riadenej úpravy pH predstavuje efektívny a prakticky aplikovateľný spôsob úpravy banských vôd. Zároveň umožňuje nielen odstránenie kontaminantov, ale aj získanie hodnotných produktov. Tým prispieva k efektívnejšiemu využívaniu zdrojov v oblastiach ovplyvnených banskou činnosťou.

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