Multi-Scale Characterization of Mine Waste in a Circular Economy: Challenges and Opportunities

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Abstract

The growing demand for critical raw materials (CRMs) for a climate-neutral economy has intensified challenges in waste generation and management. Traditional mine waste characterization, focused on environmental risk assessment within a linear economy framework ("take-make-dispose"), contrasts with the circular economy approach ("make-use-return"), which aims to minimize waste and recover valuable materials. However, unlocking the potential of mine waste requires robust, multi-scale characterization techniques. In this study, we review multi-scale characterization protocols to assess mine waste streams in support of a circular economy. In particular, we highlight the use of hyperspectral imaging as a key monitoring technique, enabling the semi-quantitative assessment of hydrogeochemical parameters and metals in mine water, identification of mineral associations in waste rock, and mapping of metal concentrations in tailings. Although challenges remain regarding sensor sensitivity, cost, and large-scale integration, addressing limitations and improving on standardization of such advanced monitoring tools can enhance mine waste management by improving environmental risk monitoring and enabling resource recovery.

Keywords: Mine waste, hyperspectral imaging, remote sensing, unmanned aerial system, tailing ponds, post-mining

Introduction

The European Union's ambition to achieve a climate-neutral economy by 2050, sustain green and digital transitions, and ensure strategic autonomy hinges on reliable, secure, and resilient access to critical raw materials (CRMs) (Ragonnaud 2023). CRMs, while not inherently scarce, are of immense economic importance for key industries. However, they face significant supply risks due to dependence on imports and a lack of viable substitutes. The growing demand for digital and green technologies has further intensified the focus on CRMs, leading to an expansion of the official list of these materials (European Commission, 2018). To meet global climate goals, mineral production may need to increase by nearly 500% by 2050 (Hund *et al.* 2020). Yet, Europe's limited mining activity for CRMs contrasts with its abundance of active and abandoned mines for other minerals. These large volumes of waste – such as waste rock, tailings, slurry ponds, and metallurgical residues – are often heterogeneous in composition and properties (Hudson-Edwards *et al.*, 2011) and are typically discarded as non-valuable, yet they may contain significant amounts of valuable CRMs (such as rare earth elements, lithium, and cobalt ore (Tayebi-Khorami *et al.* 2019)). This presents a unique opportunity to address supply challenges by revalorizing mining waste within a circular economy framework.

The transition from a linear economy model ("take, make, dispose") to a circular economy ("make, use, return") offers a transformative approach to mine waste management. In this framework, waste is minimized, and materials are continuously reintegrated into production cycles. Mining, traditionally seen as a resource-intensive industry, has the potential to play a pivotal role in advancing circular economy principles by recovering valuable materials from waste streams and reducing environmental liabilities(Schreck and Wagner 2017). Despite this possibility, the management of mine waste remains a significant challenge. Incomplete or inadequate mine closure practices can lead to severe environmental impacts, underscoring the need for improved understanding of the chemical and physical properties of mine waste. Without this knowledge, engineering solutions for waste containment and rehabilitation are likely to fail (Jamieson *et al.* 2015). Multi-scale characterization techniques, such as remote sensing, hyperspectral imaging, and geophysical methods offer promising solutions for mine waste management. However, their implementation is often limited by high costs associated with advanced sensor technologies and data processing. Early integration of these techniques throughout the mining cycle is essential for mitigating environmental risks, optimizing waste management, and advancing circular economy principles in CRMs recovery.

Methodology

In this work we explore a set of monitoring tools to characterize mine waste across different dimensions. We review innovative and sensor technology at different scales, highlighting their limitations, uncertainties, and the need for improved standardization and integration of such advanced monitoring techniques in mining operations to enhance environmental risk monitoring and enable resource recovery. Specifically, we summarize how hyperspectral imaging serves as a key technique due to its versatility and multi-scale adaptability, and show case studies that demonstrate their advantages when monitoring different mine waste constellations: semi-quantitative assessment of hydrogeochemical parameters and metals in mine water, identification of mineral associations in waste rock, and mapping of metal concentrations in tailings. A comprehensive characterization approach that requires the integration of macro, meso, and micro-scale methodologies, each providing different levels of detail (Fig. 1).

At the macro scale, large-scale monitoring techniques such as satellite imagery and airborne remote sensing enable the assessment of waste deposits and their environmental impacts. The meso scale involves site-specific assessments using drone-based hyperspectral imaging and geophysical methods to achieve detailed surface and subsurface characterization. Finally, at the micro scale, high-resolution laboratory techniques allow for the precise analysis of mineralogical, geochemical, and metallurgical properties, providing critical insights into material composition and resource recovery.

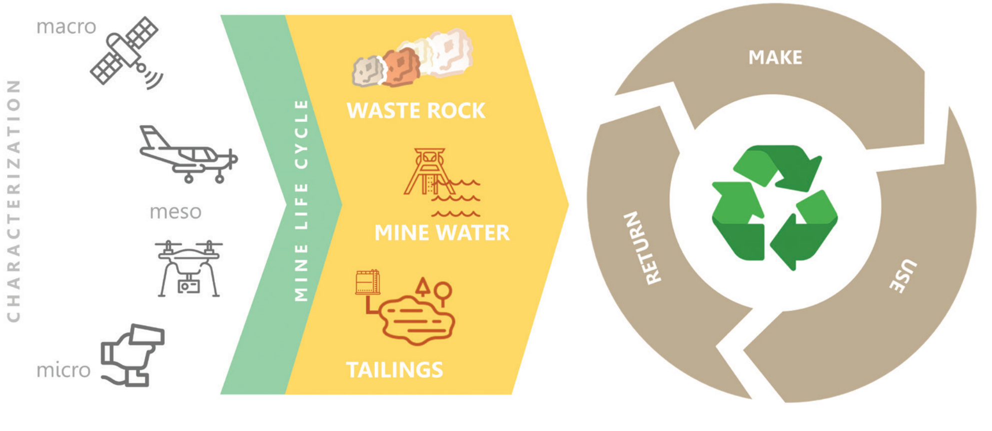

Figure 1 Schematic concept of multi-scale characterization of mine waste constellations to support a circular economy.

Macro Scale Approaches: Remote Sensing and Regional Assessments

Due to the extensive nature of mine waste, remote sensing technologies provide essential large-scale monitoring capabilities. Satellite sensors has proven effective for environmental monitoring, with hyperspectral sensors enabling the detection of metal-bearing minerals indicative of contamination. Studies have demonstrated the feasibility of using spectroscopy for detecting iron-bearing minerals in mining areas (Swayze *et al.* 2000) and for identifying acid-generating waste rock to protect water resources (Montero *et al.* 2005). More recently, hyperspectral airborne sensors have been applied to map tailings and waste materials, focusing on minerals responsible for acid formation and secondary mineral distribution (Khosravi *et al.* 2021). Reflectance spectroscopy techniques have been used to assess environmental pollution based on the presence of minerals such as jarosite, ferrihydrite, and goethite/hematite (Choe *et al.* 2008). Additionally, large-scale remote sensing studies have categorized over 1,000 waste rock dumps and tailings storage facilities worldwide (Morrill *et al.* 2022)

Meso Scale Approaches: In-Field Characterization and Geophysical Techniques

Meso-scale techniques bridge the gap between macro-scale remote sensing and micro-scale laboratory analyses, providing critical insights into the physical and chemical properties of mine waste. Hyperspectral imaging (via drones and field scanners) enables high-resolution mineralogical mapping, offering a non-invasive method for characterizing waste materials across mining sites. Geophysical methods, including Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR), and LiDAR, provide valuable subsurface information, detecting fractures, fluid movement, and material distribution (Martin *et al.* 2017). Drilling techniques (core, sonic, vibratory) allow for physical sampling, providing direct insights into stratigraphy and material properties(Benndorf *et al.* 2022; Khomiak *et al.* 2024). In-field spectroscopic analyses, such as Infrared Spectroscopy (IR) (Kamps *et al.* 2024) and portable Laser-Induced Breakdown Spectroscopy (pLIBS), enable rapid, on-site chemical characterization, reducing reliance on laboratory testing (Kuhn *et al.* 2015). Geometallurgical assessments integrate mineralogical, chemical, and metallurgical data to evaluate mine waste for CRM recovery while predicting environmental risks (Parbhakar-Fox *et al.* 2019).

Micro Scale Approaches: High-Resolution Laboratory Analyses

Micro-scale laboratory techniques are essential for detailed mine waste characterization, enabling precise assessments. Computed Tomography (CT) provides non-destructive 3D imaging of mine waste, revealing internal structures such as porosity and fractures, which are crucial for understanding leaching behavior (Jamieson *et al.* 2015). X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) identify mineral phases and elemental composition, aiding in contamination assessment and mineral stability predictions. Mineral Liberation Analysis (MLA) evaluates mineral associations for reprocessing. ICP-MS and ICP-OES provide sensitive trace element detection for monitoring hazardous metals in mine waste. Hyperspectral imaging at the laboratory scale provides detailed mineralogical mapping, supporting large-scale assessments of waste-rock dumps (Flores and Möllerherm 2023).

Results

This section presents findings from three case studies, each applying multi-scale spectral sensing technologies on different mine waste constellations. By integrating spectral characterization routines, these studies demonstrate how advanced spectral monitoring techniques can improve the characterization of different mine waste constellations. Flores *et al.* 2021 employed drone-based hyperspectral imaging to monitor acid mine drainage (AMD)-impacted river systems in the Rio Tinto region (Fig. 2). Regression analysis on hyperspectral data enabled the estimation of hydrogeochemical parameters, providing valuable insights into water quality in the Iberian Pyrite Belt, southern Spain.

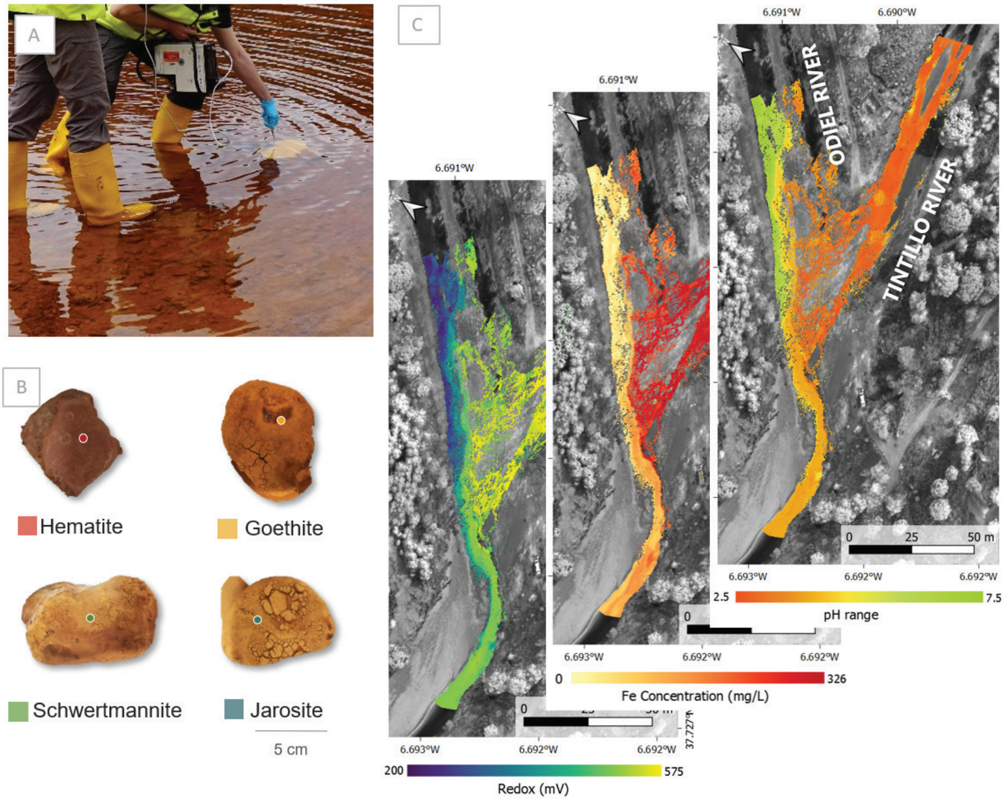

Figure 2 (A) In-field spectroscopy of Acid Mine Drainage affected waters. (B) main secondary iron-minerals detected in the river borders at the Odiel-Tintillo Confluence (southern Spain). (C) Catalogue of hydrogeochemical parameters of water derived from drone-borne hyperspectral imaging (Modified from Flores et al., 2021).

Laboratory-scale analyses of mine dumps have been conducted to assess both environmental risks and economic beneficiation (Benndorf *et al.* 2022; Flores and Möllerherm 2023). Using multiple sensors, these studies quantified metal content and identified key mineral associations (Fig. 3). A multi-method characterization approach was applied to study tailings in Ibbenbüren, Germany (Fig. 4). The workflow combined hyperspectral imaging (visible-to-near infrared and thermal), ground validation, and compositional analysis. This approach generated high-resolution mineral maps and semi-quantified iron content, identifying critical minerals associated with secondary iron by-products, which may be viable for secondary prospecting (Flores *et al.* 2024).

Conclusions

This contribution reviews various multi-scale characterization techniques applied to mine waste repositories to support both environmental monitoring and resource recovery. By integrating remote sensing, in-field spectral analysis, and laboratory-based mineralogical assessments, we demonstrate how mine water, waste rock dumps, and tailings can be effectively characterized and monitored. The results highlight the value of hyperspectral imaging for detecting hydrogeochemical parameters and metals in mine water, multi-sensor laboratory analyses for determining the composition of waste dumps, and combined imaging and geochemical methods for the semi-quantification of metal composition in tailings. Future work should focus on

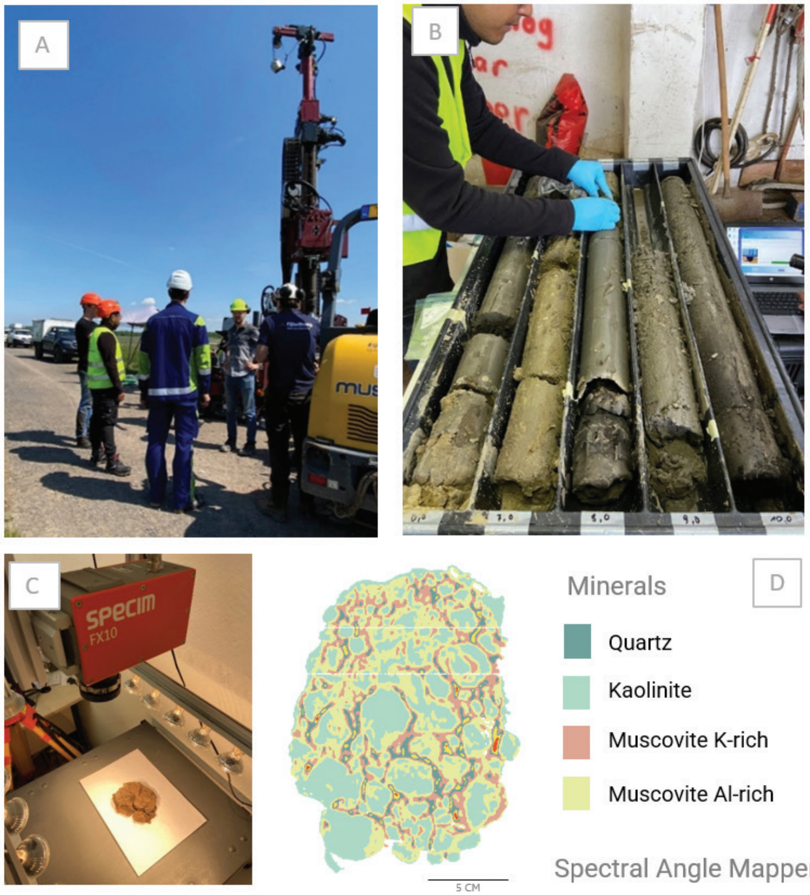

Figure 3 *(a) Drilling campaign at waste dump location. (b) Drill-core inspection and sample selection. (c) Sensor assembly at TU Bergakademie Freiberg, Department of Mine Surveying and Geodesy, Germany. (d) SAM classification over waste dump sample.*

standardizing spectral-based monitoring routines, refining pre-processing methods, and integrating machine learning for automated mineral classification. Expanding case studies to further validate the applicability and reproducibility of these techniques across different mining regions will be key to strengthening the link between characterization and reprocessing strategies, ultimately enhancing the role of mine waste management within a circular economy.

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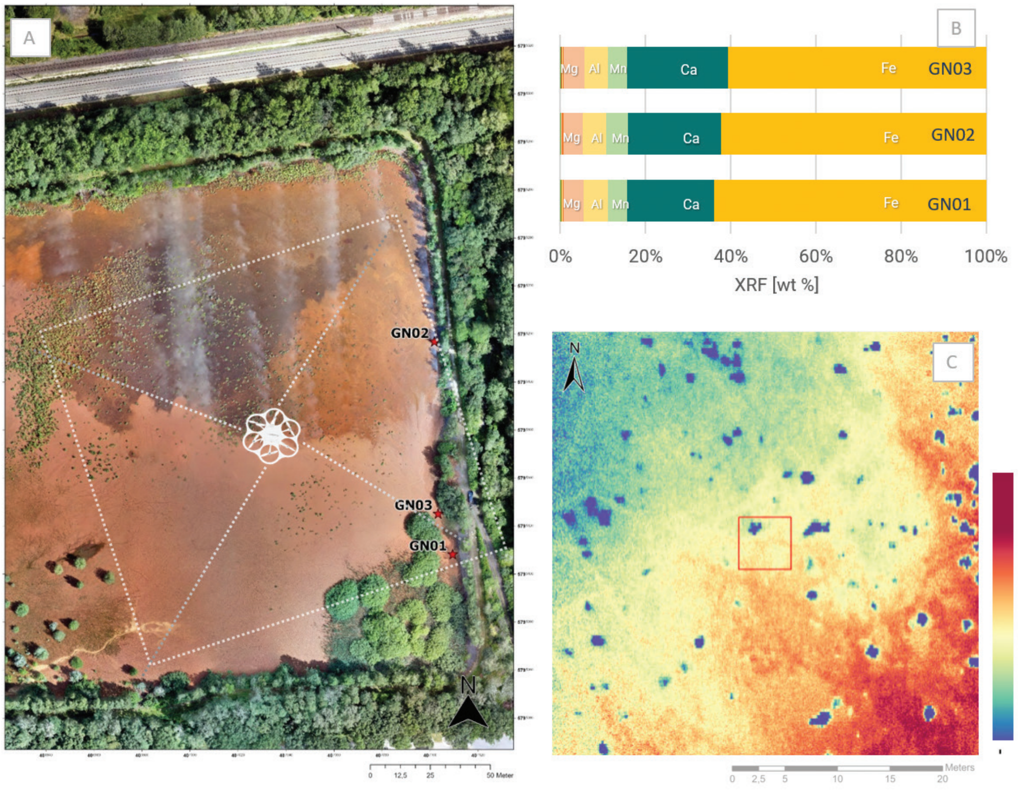

Figure 4 *(A) Orthophoto of the Tailing facility at Ibbenbüren showing the UAS-borne hyperspectral scanned scene and sampling locations (red-starts). (B) Chart of the main element fractions of three sludge samples determined by the XRF analysis. (C) Fe band ratio (650/735 nm) derived from hyperspectral scene (Modified from Flores et al., 2024).*

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