Investigation of waste-derived adsorbents for removal of NORM and non-regulated elements from mining wastewater

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Abstract The growing demand for rare earth elements (REEs) has led to an increase in mining activities, raising significant environmental concerns, particularly related to wastewater (WW) management. Mining WW can contain a complex mixture of contaminants, including naturally occurring radioactive materials (NORM), heavy metals, and organic compounds, which pose potential risks to both human health and the environment. Among various treatment approaches, adsorption is widely recognized for its simplicity, cost-effectiveness, and broad applicability. In this study, a range of adsorbents including metal-organic frameworks (MOFs), biochar, chitosan, zeolite, various biomasses, activated carbon, silica gel, and Fe_3O_4 were investigated for their potential to remove these contaminants. The goal is to evaluate and optimize the most effective adsorption process, either individually or in combination, for treating REE mining WW. This work contributes to the development of efficient, sustainable methods for mitigating the environmental impact of REE extraction.

Keywords: Adsorption, NORM, mining wastewater, REE

1. Introduction

The global demand for REEs continues to grow due to their expanding utilization across a wide range of advanced technological and industrial applications. However, these minerals must be mined, and REE mining activity requires high volumes of water that may exhibit significant environmental impact (Gajendra et al., 2025). Mining WW usually contains toxic organic pollutants (e.g. flotation reagents) and inorganic pollutants (e.g. metal ions which exceed the World Health Organization (WHO) discharge limits). Controlling the release of toxic contaminants is therefore essential to safeguard both human health and the environment. This necessitates the development of improved WW treatment strategies capable of addressing not only regulated pollutants but also NORM and non-regulated elements.

NORM that are present in the Earth's crust can become concentrated in water sources during industrial or natural processes. The global average concentrations of uranium (U) and thorium (Th) in water, contributing to exposure from natural sources, are 0.083 and 0.012 µg/L, respectively (UNSCEAR). In Europe, however, the levels in freshwater are generally higher, with U typically below 10 µg/L and Th around 0.1 µg/L (Santofimia et al., 2022). Due to its high mobility, chemical toxicity, and radiotoxicity, U is often considered one of the major contaminants. According to the WHO guidelines, the threshold of U concentration in drinking water is 30 µg/L, based on its chemical toxicity. In contrast, there are no specific concentration-based regulatory limits for Th and Radium (Ra) in drinking water. The WHO guidelines recommend a gross alpha activity limit of 0.5 Bq/L and a gross beta activity limit of 1 Bq/L to ensure radiological safety. For total Ra, compromising ^{226}Ra and ^{228}Ra isotopes, the recommended activity limit is 0.185 Bq/L (IAEA).

Non-regulated elements (e.g. Li, B, Tb) refer to those that are not currently subject to specific regulatory limits or standards by national or international authorities (e.g. EU Water Directive framework, USEPA, WHO). However, the long-term effects of these contaminants need to be taken into consideration when planning future mining activities and the necessary rehabilitation efforts afterwards.

Adsorption is an effective and economical method for wastewater treatment, widely used to remove metals, organic pollutants, and NORM (Rani et al., 2023) (Han et al., 2007). Its performance depends on the adsorbent's surface area, porosity, and reactivity (Pourhakkak et al., 2021). However, to support circular economy and address environmental concerns, there is a growing need to develop sustainable, low-cost adsorbents. These waste-based alternatives offer a promising solution by transforming waste into valuable resources for pollution control. In this study, a variety of natural, synthetic and waste-derived adsorbents, including MOF, zeolite, biochar, chitosan, activated carbon, silica, and Fe_3O_4 were investigated. With increasing focus on sustainability and circular economy practices, along with the easy access to low-cost and waste-derived materials, it's essential to thoroughly assess these adsorbents to find the most effective and environmentally friendly options for WW treatment.

2. Methods

Adsorbents mentioned in Table 1 are used for the screening experiments to investigate their adsorption efficiencies for removing NORM and non-regulated elements in the presence of other contaminants (e.g. heavy metals, organic contaminants, REEs). Synthetic water is prepared using target contaminants and mining WW conditions (e.g. pH, elemental composition in ppb to ppm range). ICP-MS/MS is used to determine the U, Th and Ra content of the surface water samples from the mining field. 50 mL flasks were used for batch-type experiments where 50-100 mg adsorbent is mixed with synthetic water at room temperature using a sample shaker at low speed. 1 mL samples were taken at adequate time intervals for 48 hours. A 50 mL flask containing synthetic water and adsorbent is centrifuged before sampling. The removal efficiency of target contaminants for different adsorbents is analyzed by ICP-MS/MS, ICP-OES and LCMS/MS.

Table 1. Adsorbents for WW treatment and target contaminants

Adsorbent	Target contaminants
MOF	Metals, radionuclides, gases
Biochar	Metals, Organic compounds
Chitosan	Metals, dyes
Zeolite	Metals, radionuclides
Activated Carbon	Organic compounds, metals, dyes, VOC
Silica Gel	VOC
Fe_3O_4	Metals, radionuclides

3. Preliminary Results

This work aims to use an adsorption process to remove NORM as well as toxic elements with or without regulatory limits. In the first step, we analyzed the synthetic water conditions, where we determined the presence of NORM in the surface water samples from the surroundings of a REE deposit (Fig. 1).

Natural background for radionuclides (U, Th and Ra) is currently below the regulatory limits (or guidelines) for drinking water, especially for Ra which was below the limit of detection (0.08 Bq/L). However, future mining activities could mobilize these elements under certain conditions, leading to enhanced levels in surface waters. Therefore, it is essential that an effective site-specific WW treatment method is readily available prior to commencing the activities.

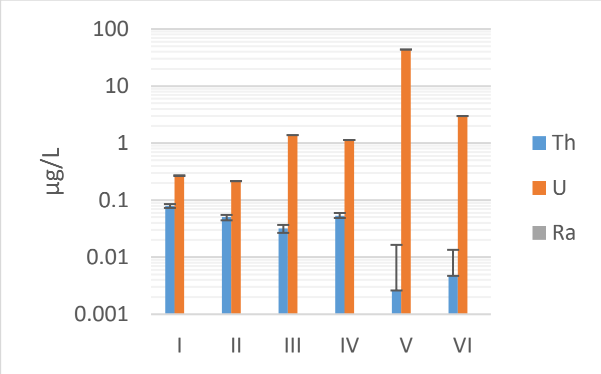

Figure 1. Natural NORM background of surface water samples surrounding a REE deposit.

4. Future Work and Outlook

We expect to have more elemental analysis of the WW resulting from different streams in the mining process and optimize our adsorption method to remove these radionuclides and non-regulated elements. In addition, the characterization of the adsorbents and the desorption mechanism will also be evaluated regarding the most effective and sustainable removal. The efficient adsorbents or absorbent combinations will be utilized for further scale-up and optimization of both column and batch-type experiments. The results of this study can benefit mining companies, decision-makers, and other WW treatment professionals by offering sustainable and environmentally friendly solutions for treating complex WW streams originating from REE mining operations.

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