Valorization of Manganese Sludge from Mine Drainage Treatment Facility: Development of Alginate-Based Adsorbent Beads for Dissolved Manganese Removal

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Abstract

Manganese (Mn) contamination in water systems presents considerable environmental and public health challenges. Although manganese is an essential trace element for human metabolism, chronic exposure can cause nervous system damage similar to Parkinson's disease, while also causing aesthetic problems such as water discoloration and unpleasant taste. Mine drainage treatment facilities often receive influent with high manganese concentrations, requiring treatment to comply with effluent discharge standards (typically ≤ 2 mg/L for dissolved manganese in clean areas). Conventional treatment using lime addition to achieve pH > 10 for manganese precipitation is energy-intensive and generates substantial sludge waste, particularly problematic for acid mine drainage (AMD) systems. The effective utilization of sludge waste generated during treatment processes represents both an environmental imperative and an opportunity for sustainable resource management in the mining sector.

This study aimed to valorize manganese sludge generated from mine drainage treatment facilities by developing alginate-based adsorbent beads through ionic cross-linking with Ca^{2+}. The effect of different drying methods (freeze-drying, oven-drying, and air-drying) on adsorption characteristics was evaluated via batch adsorption experiments. The specific surface areas of the fabricated beads were determined by nitrogen (N2) adsorption-desorption isotherm analysis using the Brunauer-Emmett-Teller (BET) equation. Bead fabrication conditions were optimized by evaluating manganese leaching behaviour and adsorption performance under varying cross-linking times (30 min, 1 h, 2 h, 6 h, 12 h) and initial pH conditions. The raw manganese sludge was characterized by X-ray powder diffraction (XPRD) for mineralogical composition and X-ray fluorescence (XRF) for elemental composition. The morphology of fabricated beads was observed by scanning electron microscopy (SEM). The maximum adsorption capacity was determined from adsorption isotherm experiments, and the adsorption mechanism and optimal contact time were elucidated through kinetic studies.

Freeze-drying preserved the porous structure and yielded both the highest specific surface area and the highest manganese removal efficiency among the tested drying methods. Leaching tests showed no manganese release at pH ≥ 4 across all cross-linking times. The optimized beads effectively removed manganese under weakly acidic pH conditions similar to actual influent, substantially improving upon conventional precipitation methods requiring pH > 10. Kinetic and isotherm analyses revealed efficient removal capacity through combined mechanisms including ion exchange, precipitation, and intraparticle diffusion.

This study presents a dual-benefit approach that simultaneously achieves waste valorization and enhanced water treatment performance. By converting manganese sludge waste from treatment facilities into functional adsorbents, this method addresses waste management challenges while reducing chemical consumption for manganese removal. The bead format enables recovery and potential reuse, facilitating practical implementation in mining wastewater treatment systems. This approach offers a sustainable solution for addressing manganese contamination in mining-affected water resources.

Keywords: Acid mine drainage (AMD), manganese sludge, alginate beads, sorption, valorization

Acknowledgements

This study was supported by the Basic Research Project of Korea Institute of Geoscience and Mineral Resources (Project code: 26-3414).