Evaluating the Sustainability of Passive Treatment for Acid Mine Drainage of a Legacy Mine via Life Cycle Assessment

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Abstract

Legacy Mine X in Japan has employed an active treatment system since 1979, generating high CO_2 emissions and operational costs. In 2021, a pilot-scale passive bioreactor achieved 98% manganese (Mn) and zinc (Zn) removal, but the comprehensive environmental impact assessment has not been yet evaluated. Using life cycle assessment (LCA), the passive treatment system was found to emit approximately 130 g CO_2 equivalent/m^3, with a unit cost of 37.91 Japanese Yen/m3. Scaling up passive treatment presents a sustainable and cost-effective remediation strategy.

Introduction

The active treatment system at Legacy Mine X has effectively prevented mine drainage from contaminating surrounding water bodies and aquatic environments, although at a high cost (Hengen *et al.* 2014; Miyata *et al.* 2024). To reduce operational expenses and CO_2 emissions, passive treatment was introduced to the study area. The pilot-scale passive treatment successfully removed Mn and Zn from the mine drainage using limestone gravel to enhance the activity of Mn-oxidizing bacteria (Watanabe *et al.* 2024). However, the environmental impacts, particularly CO_2 emissions and operational and maintenance costs of scaling up the passive treatment system have not yet been fully investigated. Therefore, this study employs LCA of the full-scale passive treatment system scenarios to estimate the CO_2 emission and operational cost of the passive treatment.

Methods

Full-scale passive treatment scenario

The full-scale passive treatment plant scenario was designed to treat mine drainage at an average flow rate of 2.84 m^3/s (Iwasaki *et al.* 2022) (Fig. 1), based on the pilot-scale passive treatment described in Tum *et al.* (2024). The system is designed to operate on a daily basis for at least 30 years. Regular maintenance is planned every three years to remove the formation of birnessite and woodruffite coatings on the limestone surface, which could otherwise affect the efficiency of the system.

Life cycle assessment approach

The assessment uses a midpoint evaluation method to focus on CO_2 emissions, using kilograms of CO_2 equivalent per m3 (kg CO_2 eq/m^3) as the functional unit during the operational period. The system boundaries include all aspects of the treatment plants, such as energy consumption, water sampling, sample handling, transportation, sludge management, and labour. Operation and maintenance costs are included in the LCA to facilitate economic comparison. In addition, the study explores strategies to reduce CO_2 emissions in the passive treatment system using the alternative energy sources. The cost of the active treatment system was determined based on annual mine drainage treatment costs and the volume of mine drainage treated.

Result and discussion

The mine drainage at the study site contained Mn and Zn concentrations of 20 mg/L and 8 mg/L, respectively (Watanabe *et al.* 2024). The pilot-scale passive treatment system exhibited removal efficiencies of 98% for Mn and 82% for Zn, attained with a hydraulic retention time (HRT) of 0.5 days within the limestone tank (Tum *et al.* 2024). These removal rates signify the system's capacity to adhere to regulatory mandates for treated mine drainage.

The LCA study revealed that the passive treatment system emits approximately 97,000 kg CO_2 equivalent annually, with an operational cost of 28.2 million JPY. By comparison, the active treatment system is more resource-intensive, costing approximately 147 million JPY annually (METI 2010). Furthermore, the unit processing cost of the passive system (37.91 JPY/m^3) is 2.6 times lower than that of the active system (99.5 JPY/m^3), underscoring its economic viability.

The transition to nuclear or solar energy has the potential to enhance the environmental and economic sustainability of the passive system (Fig. 2). It is important to note, however, that while nuclear energy sources have been posited as a means to minimize CO2 emissions, this is an option that has been largely overlooked since the 2011 Fukushima nuclear incident (Yamagata 2024). Conversely, the utilization of solar energy has been shown to result in a 16,210 kg CO_2 eq annual reduction in CO_2 emissions, accompanied by a 10 million JPY annually decrease in energy expenditures. This finding underscores the importance of energy source selection in reducing the carbon footprint and operational expenses of passive treatment systems (Fig. 2).

Despite its apparent advantages, the passive system faces challenges related to maintenance. The necessity of limestone replacement every three years results in substantial expenditures and CO_2 emissions. Nevertheless, the negative environmental impacts of the passive system remain comparatively less substantial than those associated with the active system. This is primarily due to the reduced consumption of raw materials and the consequent decrease in greenhouse gas emissions.

Conclusion

The findings indicate that expanding the passive treatment system offers a sustainable and cost-effective solution for mine drainage remediation. The associated reductions in CO2 emissions and treatment costs are highly beneficial to mine wastewater operations

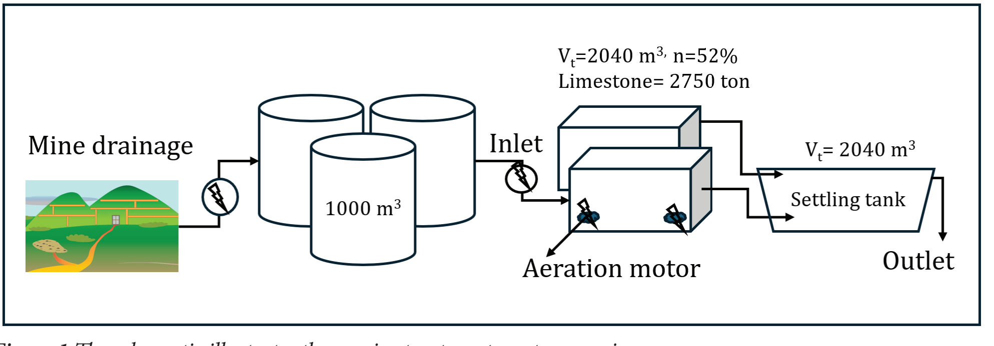

Figure 1 *The schematic illustrates the passive treatment pants scenario.*

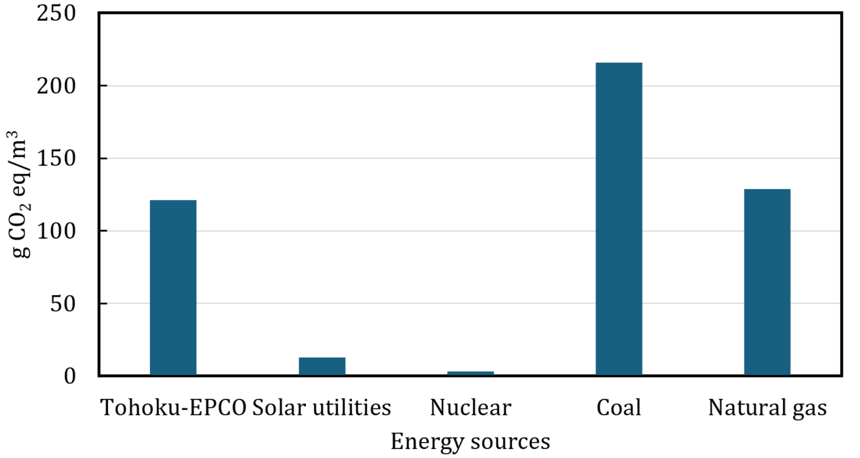

***Figure 2** CO_2 emissions from the passive treatment plant during the treatment of 1 m^3 of mine drainage according to various energy sources, Tohoku-EPCO: a local electric company in the Tohoku region, Japan.*

and align with the CO_2 zero-emission goals. Future research should prioritize optimizing maintenance practices and further reducing energy consumption to enhance the long-term viability of the system. Additionally, evaluating the applicability of this approach to other legacy mine sites will be essential to assess its broader scalability and impact.

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