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Development of a CO_2 Accounting Methodology for Acid Mine Drainage Treatment Processes and CO_2 Emission Assessment of Real Sites

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Abstract

A comprehensive CO_2 accounting method based on carbon mass balance was developed for active acid mine drainage treatment plants. Five emission scopes are defined, covering treatment, internal and external transport, power, and chemical production. Applied to four Japanese plants ranging in scale and using different neutralizers, the results show that calcium-based neutralizers and electricity use dominate emissions. $Ca(OH)_2$ systems can absorb CO_2 under high pH conditions. The method enables plant-specific and cross-plant comparisons, providing a practical framework for decarbonization strategies in the acid mine drainage treatment sector. A CO_2 calculation method was developed and applied to AMD passive treatment system.

Keywords: Acid mine drainage, treatment, CO_2 emission, carbon neutrality

Introduction

Acid mine drainage (AMD) is generated by the oxidation of sulfide minerals during mining activities. These solutions are characterized by low pH and elevated metal concentrations, necessitating their long-term treatment prior to discharge. Active treatment systems that employ alkaline neutralizers, such as limestone ($CaCO_3$) and hydrated lime ($Ca(OH)_2$), are widely used due to their operational reliability and high capacity. These processes are, however, inherently carbon-intensive, because CO_2 is emitted during lime production (calcination), in the neutralization reactions, and owing to electricity generation. Active AMD treatment plants are therefore potential long-term point sources of CO_2 emissions.

Globally, many countries have committed to achieving carbon neutrality by 2050 (IEA 2023). The Japanese government has proposed policies for economic treatment of AMD and aims to achieve carbon neutrality in this industry by 2050 (Ministry of Economy 2023).

Previous studies in South Korea and Germany reported substantial CO_2 emissions from AMD treatment, mainly associated with neutralizer production and application (Kim *et al.* 2025; Totsche *et al.* 2025). Emissions have also been estimated using life cycle assessment and standardized inventory methodologies provided by the Intergovernmental Panel on Climate Change (IPCC 2006). While these approaches offer useful estimates, they rely on generalized emission factors or national-level accounting frameworks that do not fully capture plant-specific operational conditions and inorganic carbon (IC) transformations. To achieve carbon neutrality in the AMD treatment sector, facility-level and process-resolved CO_2 accounting is essential.

This study developed a site-specific CO_2 accounting framework for active AMD

treatment plants based on carbon mass balance, enabling precise quantification of direct and indirect emissions. Unlike conventional methods, it explicitly captures IC transformations and plant-specific operational characteristics, evaluated at four representative active AMD treatment plants in Japan. Its implications for achieving carbon neutrality in the AMD treatment sector are discussed.

Methods

System boundaries

System boundaries were defined to quantify CO_2 emissions from active AMD treatment processes by distinguishing direct and indirect sources (Figure 1). Direct emissions (Scope 1) include CO_2 released during neutralization reactions and biological processes occurring between AMD inflow and treated effluent discharge. Indirect emissions (Scopes 2 and 3) comprise electricity generation and emissions associated with production and transportation of the alkaline neutralizers.

Because flocculant dosage is minor and their manufacturing data are limited, flocculant production is excluded, but its transportation is included. CO_2 exchange during treatment is governed by pH-dependent carbonate equilibria, and direct measurement of gas fluxes is rarely conducted in AMD plants; therefore, CO_2 emissions within the defined boundary were estimated using a carbon mass balance approach that accounts for IC transformations during the neutralization process.

Calculation formula

Active AMD treatment site

CO_2 emissions for active AMD treatment were calculated using the difference between the carbonate inputs and outputs. CO_2 emissions related to transportation, electricity consumption, fossil fuel combustion, and chemical reagent production were calculated using the respective total masses and their specific emission factors (EF).

1. Direct emissions

Total inorganic carbon (TIC) values of the influent (in), effluent (out), and sludge (S) were used to represent IC distribution within the system:

$$M_{T-CO_2} = [(V_{in} \times C_{in-C} \times m_{CO_2}/m_C \times 10^{-6}) + (M_N \times P_N/100 \times m_{CO_2}/m_N)] - [(V_{out} \times C_{out-C} \times m_{CO_2}/m_C \times 10^{-6}) + (M_S \times C_{S-TIC} \times m_{CO_2}/m_C \times 10^{-3})], \quad (1)$$

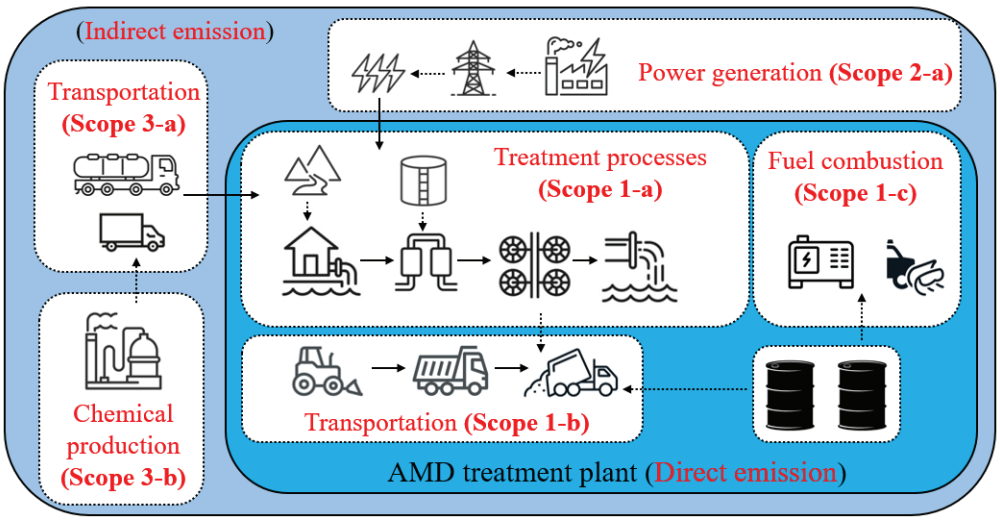

Figure 1 System boundaries for CO_2 emission scopes from an acid mine drainage (AMD) treatment plant.

where V_i(m³), C_i(mg/L), m_i(g/mol), M_i(t) and P_i(%) represent volume of influent and effluent, concentration of IC in influent, effluent and sludge, molar mass, weight of neutralizer and sludge and purity of neutralizer respectively.

Emissions from on-site fuel combustion (vehicles and machinery) were calculated as:

$$M_{fuel-CO_2} = \sum_i V_{\text{fuel}-i} \times EF_{\text{fuel}-i}, \quad (2)$$

where V(L) and EF(kg – CO_2/L) represent volume of fuel and emission factor of each fuel type respectively.

2. Indirect emissions

Indirect emissions include electricity consumption and upstream processes. EF were obtained from national inventory databases and supplier-specific data.

Electricity consumption-related emissions were estimated by:

$$M_{power-CO_2} = P_{\text{Total}} \times EF_{\text{Power}}, \quad (3)$$

where P(kWh) and EF(kg – CO_2/kWh) represent amount of purchased electricity and emission factor of each grid respectively.

Emissions from transportation of reagents were calculated as:

$$M_{vehicle-CO_2} = \sum_i D_{\text{vehicle}-i} \times EF_{\text{vehicle}-i}, \quad (4)$$

where D(km) and EF(kg – CO_2/ km) represent distance of transportation and emission factor of each vehicle type respectively.

Emissions from chemical manufacturing were estimated by:

$$M_{con.-CO_2} = \sum_i M_{\text{con.}-i} \times EF_{\text{con}-i}, \quad (5)$$

where M(t) and EF(t – CO_2/t) represent weight of each chemical reagent and emission factor of its production respectively.

Passive AMD treatment site

Carbon fluxes within a passive AMD treatment system are defined as shown in Figure 2. AMD enters the system carrying dissolved inorganic carbon (DIC), which is transported along the flow path and transformed through gas exchange, carbonate precipitation, and biological processes. Elevated pH promotes CO_2 absorption and carbonate formation in the substrate; plants and microorganisms convert DIC into organic carbon (OC) and mediate its mineralization. These processes govern carbon partitioning between aqueous DIC, biomass, carbonate solids, and atmospheric CO_2 within the passive treatment system.

Annual CO_2 emissions from passive AMD treatment systems were estimated using a system-boundary carbon mass balance approach. The calculation integrates: (i) DIC fluxes associated with influent and effluent AMD, (ii) temporal changes in solid-phase carbon stocks, including substrates and accumulated sludge, and (iii) biomass carbon accumulation and removal due to plant growth and harvesting. Total emissions from

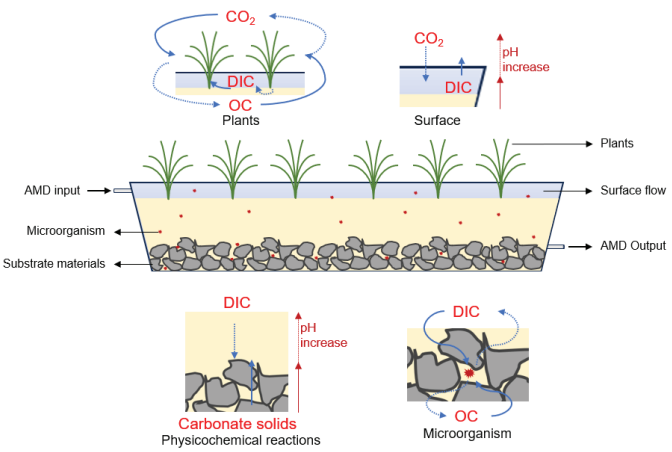

Figure 2 Carbon flow in a passive acid mine drainage treatment system.

n years were annualized based on the total operational duration:

$$M_{T-CO_2} = \left[(V_{in} \times C_{in-IC} + V_{out} \times C_{out-IC}) + \frac{(M_{S-initial} \times C_{S-initial-TC} - M_{S-final} \times C_{S-final-TC})}{n} + (M_{P-initial} \times C_{P-initial-TC} - \sum_i M_{P-cut} \times C_{P-cut-TC})/n\right] \times \frac{m_{CO_2}}{m_C} \times 10^{-6}, \quad (6)$$

where V_i(m³), C_i(mg/L), M_i (t), n and m_i(g/mol) represent volume of influent and effluent, concentration of C in influent, effluent, substrates and plants, weight of substrates and plants, molar mass and total operation year respectively.

The framework is applicable to typical passive AMD treatment configurations, including open drains and constructed wetlands, where hydraulic inflow–outflow, sediment accumulation, and optional vegetation constitute the carbon fluxes.

Study sites and data sources

Four full-scale active AMD treatment plants in Japan (Plants A–D) were selected to evaluate plant-level CO_2 emissions. All facilities apply neutralization–sedimentation processes but differ in operational scale, neutralizer type, and sludge management practices. Plants A and D use $Ca(OH)_2$, Plant C uses ground $CaCO_3$, and Plant B applies both materials. These variations reflect differences in influent flow rate, initial water chemistry, and site-specific design, making the selected plants representative of typical active AMD treatment systems currently operating in Japan. One passive AMD treatment site in Japan was evaluated. This site treats AMD in open drain flow and precipitation pools. The volumes treated and metals concentrations are much lower than those of the active treatment plants.

Operational data, including AMD flow rate, electricity consumption, chemical usage, and sludge production, were obtained from official governmental records (JOGMEC 2025). Carbon-related parameters of the water and sludge were determined by on-site sampling and laboratory analysis of TC. The combination of operational records and measured carbon data ensured consistent and reliable input for the plant-specific CO_2 accounting framework.

Results and discussion

Yearly CO_2 emissions from active acid mine drainage treatment plants

1. Yearly total and average emissions

Annual CO_2 emissions for April 2023–March 2024 were calculated using this accounting framework. Total emissions differed substantially between the four plants due to variations in treatment scale, influent chemistry, neutralizer type, and electricity consumption.

Table 1 *Annual CO_2 emissions by scope in different active acid mine drainage treatment plants (Unit: t).*

Scope	Plant A	Plant B	Plant C	Plant D
1a Treatment	−0.34	942.62	2602	−4.04
1b and 1c Internal transportation and other	3.76	59.63	99.13	1.15
2a Power generation	56.92	761.02	1582	27.86
3a External transportation	1.71	8.11	33.93	0.22
3b Chemical production	103.1	275.71	16.89	3.43
Total	165.1	2047	4334	28.62

As shown in Table 1, Plant C had the highest total annual emissions; Plant D had the lowest. Emission ranking generally followed neutralizer type and consumption: Plants B and C, which used powdered $CaCO_3$, exhibited significant direct emissions from carbonate decomposition under acidic conditions, plant B utilized both $CaCO_3$ and $Ca(OH)_2$ and resulted in higher emissions from chemical production than Plant C; in contrast, Plants A and D used $Ca(OH)_2$, and negative values were observed for Scope 1a, indicating net CO_2 uptake during treatment. This uptake was attributed to high pH conditions that promote atmospheric CO_2 dissolution and potential microbial fixation (Vesper *et al.* 2016). The treated water showed a pH comparable to that of the receiving natural water bodies, and most sludge is managed within the treatment facility. Therefore, the risk of immediate CO_2 re-release is considered limited, although its long-term stability remains uncertain.

2. Distribution of CO_2 emissions by scope

The distribution of emissions by scope reveals that indirect emissions dominated in most cases. For Plant A, approximately 98% of total emissions originated from electricity consumption and chemical production. In Plants B and C, direct emissions from neutralization contributed 46%–56% of total emissions, reflecting the influence of carbonate-based reagents.

When neutralizer-related emissions (Scopes 1a and 3b) were combined, they accounted for approximately 60% of total emissions in Plants A–C. Electricity consumption contributed about 36% on average, while transportation and other activities represented less than 5%. In Plant D, high final pH and low neutralizer demand resulted in net negative neutralizer-derived emissions, and electricity became the dominant source.

Overall, neutralizer selection was the primary determinant of emission structure, followed by electricity consumption. Transportation contributed minimally in all cases. The relative contribution of electricity-related emissions would vary depending on the electricity mix, and it would decrease substantially with transition toward a low-carbon grid.

Carbon flow during active acid mine drainage treatment

Carbon flux analysis (Table 2) shows that IC conversion to OC occurred in all plants; however, the influence on total direct emission estimates was limited. Differences between the simplified mass balance calculation and detailed carbon flux analysis were below 9% except for Plant A, where higher microbial conversion affected net direct emissions (Ishii *et al.* 2015; Huang *et al.* 2025).

Plants using $CaCO_3$ (B and C) showed increased dissolved TIC in the effluent due to carbonate dissolution, whereas Plants A and D exhibited greater potential for atmospheric CO_2 uptake under higher pH conditions. Although IC conversion introduces minor uncertainty, its contribution is small relative to emissions from electricity and neutralizer production. Therefore, excluding detailed IC–OC conversion has limited influence on total emission estimates for most plants.

In the passive treatment system, CO_2 is emitted in the open drain flow from the generating point source to the precipitation tank; however, CO_2 is absorbed during the precipitation process. This result indicates

Table 2 *Mass distributions of total carbon (TC), total inorganic carbon (TIC), and total organic carbon (TOC) in active acid mine drainage treatment plants (Unit: t).*

Plant	A			B			C			D		
Carbon	TIC	TOC	TC	TIC	TOC	TC	TIC	TOC	TC	TIC	TOC	TC
Output	0.56	1.93	2.48	20.39	18.47	38.86	33.12	23.83	56.95	1.12	0.18	1.29
Input	0.47	0.28	0.76	277.5	4.51	282.0	743.8	16.86	760.7	0.02	0.07	0.09

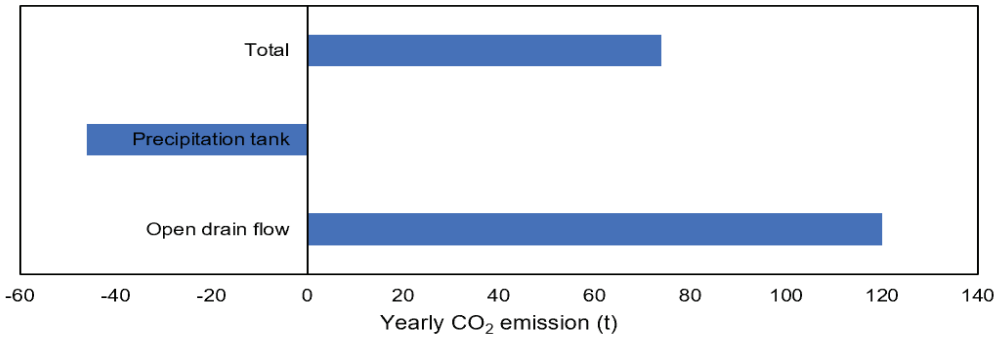

Figure 3 *Yearly CO_2 emissions of passive acid mine drainage treatment site.*

that oversaturated CO_2 in the original AMD would be released during open drain flow. In the precipitation tank, CO_2 would be absorbed due to the higher pH value and possible microbial activities. The treatment duration is much longer than active treatments, which allows potential for absorption of more CO_2 from the atmosphere and its storage in effluent and sludge.

For passive treatment systems without open drain flow (not including the treatment process), the total CO_2 emissions could be lower and may even have the possibility of achieving CO_2 absorption.

Conclusions

Carbon neutrality in all industries is essential, and decarbonizing AMD treatment is a key step. This study developed a CO_2 accounting method for active AMD treatment plants, covering five emission scopes: treatment, internal and external transportation, power generation, and chemical production. Applied to four operating plants of ranging scales and using different neutralizers, the method identified calcium-based neutralizers and electricity use as dominant emission sources, with indirect emissions prevailing. Inter-plant differences mainly reflect neutralizer type and operational configuration. In $Ca(OH)_2$-based systems, CO_2 alternated between emission and uptake: IC–OC conversion could cause overestimation. To achieve the carbon neutrality target for power generation by 2050, decarbonization should focus on use of alternative low-carbon neutralizers and optimized treatment capacity. This plant-specific framework enables cross-plant comparison and longitudinal analysis, supporting evidence-based mitigation strategies for AMD treatment. Passive treatment systems have lower CO_2 emissions than active systems and have higher possibility of achieving zero emission or even absorption.

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