Field Demonstration of Solar-Powered Iron Electrocoagulation for Arsenic-Contaminated Mine Drainage at the Geumjeong Abandoned Mine, Korea

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Abstract

Arsenic-rich drainage from the Geumjeong Gold Mine in Gyeongsangbuk-do, South Korea, contains 300–500 µg/L of arsenic, exceeding drinking-water standards by up to 50 times. A solar-powered iron electrocoagulation (Fe–EC) system was installed to evaluate field performance under real mine-water conditions. The modular unit, consisting of dual EC reactors and an expanded polystyrene (EPS) filtration stage, treated 8 m^3/day at 4.6 A and 2.3 V. Arsenic concentrations decreased below 10 µg/L within 20 minutes and stabilized at <5 µg/L after one hour, achieving >99% removal. Power consumption remained below 100 W, confirming suitability for decentralized, off-grid mine-water treatment applications.

Keywords: Arsenic, solar-power, electrocoagulation, mine drainage

Introduction

Arsenic (As) is a naturally occurring metalloid widely distributed in geological environments and groundwater systems (Ahn *et al*. 2007; Smedley and Kinniburgh 2002). Long-term exposure to arsenic is associated with severe health effects, leading the World Health Organization (WHO) to establish a drinking-water guideline of 10 µg/L (WHO 2004; Smith *et al*. 2002). In groundwater and mine drainage, arsenic mobility is strongly controlled by redox and pH conditions. Under reducing environments, As(III) predominates as neutral H_3AsO_3 and exhibits high mobility and low adsorption affinity. Under oxidizing conditions, As(V) forms negatively charged oxyanions ($H_2AsO_4^-$, $HAsO_4^{2-}$) that are more readily adsorbed onto iron hydroxides.

Conventional arsenic removal methods—including chemical coagulation, adsorption, ion exchange, and membrane filtration—often require chemical reagents, skilled operation, and stable power supply. Because As(III) is more difficult to remove than As(V), pre-oxidation is frequently necessary. Electrocoagulation (EC) generates iron hydroxides in situ via anodic dissolution and can simultaneously promote partial oxidation of As(III), reducing the need for chemical addition (Ji *et al*. 2011; Wan *et al*. 2011). EC systems are compact, relatively simple, and produce lower sludge volumes compared with conventional processes.

Despite promising laboratory results, field-scale validation of EC under real mine-water conditions remains limited. The Geumjeong Gold Mine in Bonghwa-gun, South Korea, discharges arsenic-rich drainage exceeding regulatory standards. This study evaluates the performance, energy efficiency, and practical applicability of a solar-powered iron electrocoagulation system for treating arsenic-contaminated mine drainage under field conditions.

Electrocoagulation Mechanism

Electrocoagulation (EC) is an electrochemical treatment process in which sacrificial metal electrodes, typically iron or aluminum, dissolve under an applied electric current to generate coagulant species in situ. In iron-based systems, anodic dissolution releases ferrous and ferric ions, which subsequently hydrolyze to form amorphous iron hydroxides with high surface area and strong adsorption capacity (Mollah *et al.* 2001; Emamjomeh and Sivakumar 2009).

At the anode, iron oxidation occurs according to:

$$Fe \rightarrow Fe^{2+} + 2e^{-}$$

Ferrous ions may further oxidize to Fe^{3+} in the presence of dissolved oxygen. These ions hydrolyze to produce $Fe(OH)_2$ and $Fe(OH)_3$ precipitates, forming reactive flocs capable of adsorbing and co-precipitating dissolved contaminants. In arsenic-containing waters, arsenate species (As(V)) are effectively adsorbed onto iron hydroxides through surface complexation reactions, while arsenite (As(III)) may be partially oxidized during the electrochemical process, enhancing removal efficiency (Kumar *et al.* 2004).

At the cathode, hydrogen evolution occurs:

$$2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-}$$

The generation of hydroxide ions increases local pH near the electrode surface, promoting iron hydroxide precipitation and floc formation. The combined effects of electrochemical dissolution, oxidation, adsorption, and flotation contribute to efficient contaminant removal without external chemical addition. These mechanisms make iron electrocoagulation particularly suitable for decentralized treatment of arsenic-rich mine drainage.

Methods

The field demonstration was conducted at the Geumjeong Gold Mine in Bonghwa-gun, Gyeongsangbuk-do, South Korea (Figure 1). The mine historically produced gold, silver, and iron until mining rights expired in 1988. The site currently discharges mine drainage

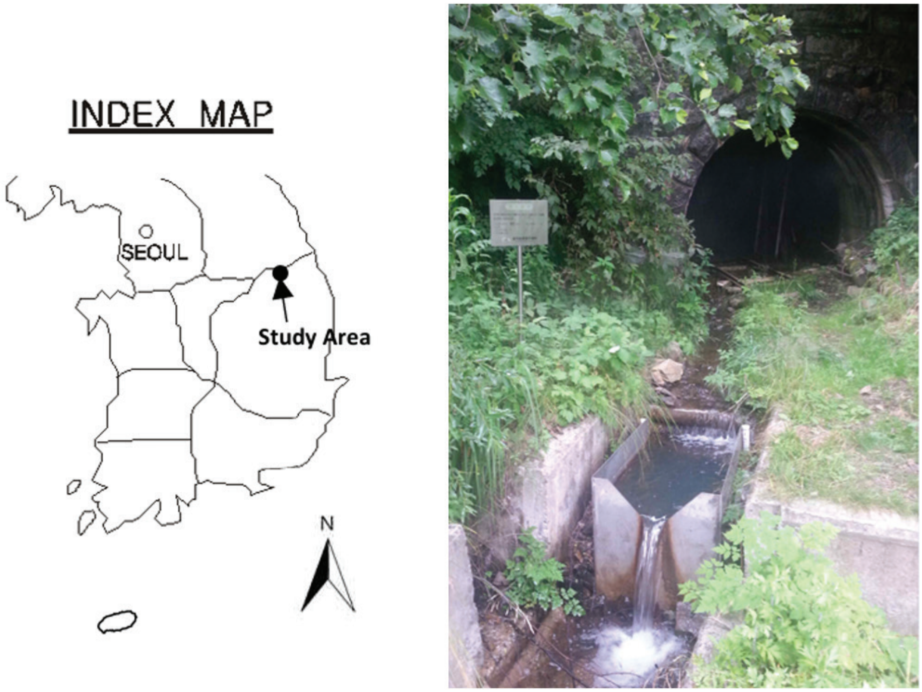

Figure 1 Study area map and mine drainage discharge at the Geumjeong abandoned mine, South Korea.

under oxidizing conditions, characterized by slightly alkaline pH (8.6–8.7), elevated oxidation–reduction potential (ORP), and high dissolved oxygen (DO) concentrations. Arsenic concentrations ranged from approximately 400 to 500 µg/L, exceeding the World Health Organization (WHO) drinking-water guideline of 10 µg/L by 40–50 times.

A stand-alone, solar-powered EC system was installed and operated as a field-scale demonstration unit under actual mine drainage conditions. The system consisted of photovoltaic panels, EC reactors, an expanded polystyrene (EPS) filtration unit, and a clean-water storage tank (Figure 2). Electricity generated by the solar panels powered a submersible pump that transferred raw mine drainage to the influent tank. To maximize energy efficiency, water movement between subsequent treatment units was driven by gravity using hydraulic head differences. The entire system was constructed in a modular, container-based configuration to facilitate transport and installation in remote mining areas lacking grid power.

Three EC reactors were installed to allow modular expansion and operational flexibility under variable mine drainage conditions. During the present field trial, two reactors were operated because the influent flow rate was sufficiently treated within the target hydraulic retention time using dual-reactor operation. Influent water was evenly distributed to the reactors in parallel flow. Each reactor contained seven iron electrodes (470 mm × 100 mm × 3 mm) arranged alternately as three anodes and four cathodes. The electrodes were mounted in a detachable cartridge structure to allow easy maintenance and replacement, with an estimated service life of approximately one year under the applied operating conditions. Mine drainage entered from the bottom of each reactor and flowed upward. During operation, anodic dissolution released iron ions that formed iron hydroxide flocs, which adsorbed and co-precipitated dissolved arsenic species.

Downstream of the EC reactors, an EPS foam filtration unit was installed to remove suspended flocs. Water flowed upward through the floating EPS media, which physically retained iron–arsenic precipitates. The filtration unit was equipped with a bottom discharge outlet to allow periodic removal of accumulated sludge without significant performance deterioration.

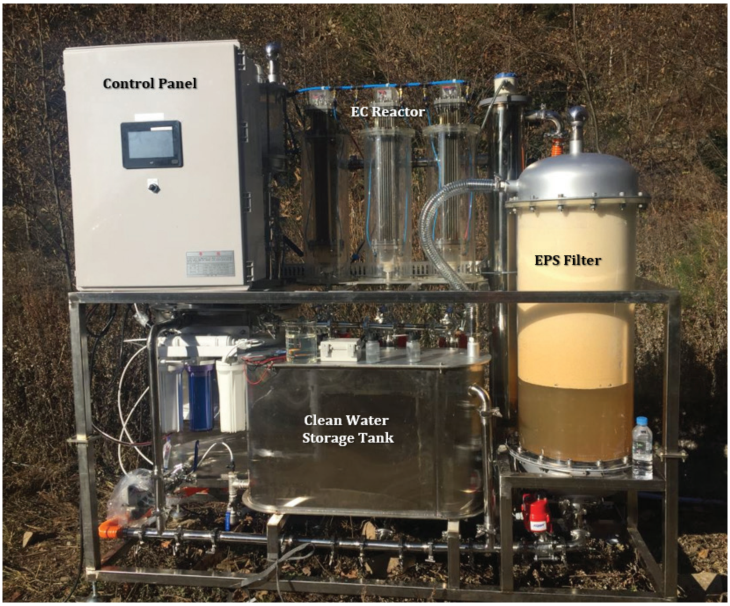

***Figure 2** Field-scale electrocoagulation (EC) system installed at the Geumjeong Gold Mine.*

During the field demonstration, the system operated at a treatment capacity of 8 m³/day (approximately 2.8 L/min per operating line), with an applied voltage of 2.3 V and a current of 4.6 A supplied by photovoltaic power. The treatment capacity corresponded to approximately 16–80% of the mine drainage discharge (10–50 m³/ day), depending on seasonal flow conditions. The system was therefore designed as a modular field-demonstration unit to evaluate scalability under real mine-water conditions.

Results and Discussion

Field-scale operation demonstrated rapid and stable arsenic removal performance. Within 20 minutes of system start-up, treated water arsenic concentrations decreased below the WHO drinking-water guideline of 10 µg/L (WHO 2004). After one hour of continuous operation, concentrations stabilized at <5 µg/L, confirming removal efficiencies greater than 99% from initial levels (~400– 500 µg/L). The fast stabilization indicates effective iron hydroxide floc formation and strong adsorption–co-precipitation mechanisms under slightly alkaline and oxidizing mine-water conditions, consistent with previously reported EC removal mechanisms (Mollah *et al.* 2001; Kumar *et al.* 2004).

The observed removal kinetics are comparable to previously reported electro-coagulation studies. Kobya *et al.* (2016) achieved compliance with drinking-water standards within 13 minutes under optimized current density conditions, and Das and Nandi (2021) reported similar removal efficiencies within 20 minutes in laboratory-scale systems. Notably, the present study achieved comparable reaction rates under field-scale conditions treating approximately 8 m³/day of actual mine drainage, demonstrating the practical scalability of the system beyond laboratory validation.

The use of iron electrodes proved particularly suitable for arsenic removal. Iron hydroxide flocs are known to exhibit strong adsorption affinity for arsenate species (Smedley and Kinniburgh 2002). Comparative studies indicate that Fe electrodes perform as well as or better than aluminum electrodes for arsenic removal (Tenodi *et al.* 2024). In the present system, electrochemically generated iron ions formed dense hydroxide precipitates that effectively captured dissolved arsenic. Furthermore, electrochemical processes can promote partial oxidation of As(III) to As(V), enhancing removal efficiency without the need for external oxidants (Kumar *et al.* 2004; Emamjomeh and Sivakumar 2009). This characteristic represents a significant advantage in remote mine sites where chemical dosing is impractical.

Energy demand remained below 100 W throughout operation, confirming that the system can be fully powered by photovoltaic panels. Such low energy requirements are consistent with decentralized electrochemical treatment systems reported in recent modular water-treatment studies (Castañeda *et al.* 2024). The modular, container-based configuration further enhances field applicability by enabling rapid deployment and scalability. Compared to adsorption-based systems that require periodic media replacement, electrocoagulation continuously generates fresh coagulant in situ (Mollah *et al.* 2001). The projected electrode lifespan of approximately one year reduces maintenance frequency and operational costs, increasing suitability for long-term management of abandoned mine drainage.

Overall, the field validation confirms that solar-powered iron electrocoagulation is a technically robust, energy-efficient, and scalable solution for treating high-arsenic mine drainage. The results demonstrate that electrocoagulation can move beyond laboratory-scale research toward practical implementation in decentralized and infrastructure-limited environments.

Conclusions

This study demonstrated the field applicability of a solar-powered iron electrocoagulation (Fe–EC) system for treating arsenic-contaminated mine drainage at the Geumjeong Gold Mine, South Korea. The system reduced arsenic concentrations from 400–500 µg/L to below 10 µg/L within 20 minutes and stabilized at <5 µg/L after one hour, achieving removal efficiencies exceeding 99%.

Electrochemically generated iron hydroxide flocs effectively adsorbed and co-precipitated dissolved arsenic without the need for external chemical addition. Total energy consumption remained below 100 W, confirming the feasibility of fully photovoltaic-powered operation in remote mining areas.

The modular configuration, low maintenance demand, and projected one-year electrode lifespan highlight the practicality of this approach for decentralized remediation of abandoned mine drainage. These results support the transition of iron electrocoagulation from laboratory research to sustainable field implementation.

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