

# The use of electrokinetics promises a sustainable mining future

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Moving toward a zero-carbon economy is an ambitious goal of all human beings. Utilization of various metal resources plays a central role in such a transition. Rare earth elements (REEs), especially heavy REEs (HREEs), are crucial for the development of future green and zero-carbon economies due to their irreplaceable roles in many applications of renewable energy technologies; e.g., solar panels, wind turbines, and hybrid vehicle batteries. Ion-adsorption rare earth deposits (IADs) are the primary repositories for HREEs and supply more than 95% of the global HREE demand.<sup>1</sup> However, current mining technologies using excessive ammonium salts have caused devastating harm to the local environment while exhibiting a low recovery rate of REEs, a long mining period, and landslide risks. Since 2018, the adoption of ammonium salt-based techniques in REE mining has been prohibited, exacerbating the scarcity of REEs that could lead to disruptions of the supply chain. Moreover, metals are currently almost exclusively extracted from their ores via physical excavation or chemical leaching. These energy-intensive and environmentally damaging techniques remain among the foremost CO<sub>2</sub> emitters. The mining industry is in desperate need of a new generation of mining technology.

Here, we introduce an advance in the development of a new electrokinetic mining (EKM) technology that can simultaneously help reduce the environmental impacts and improve the recovery rate of REEs (Figure 1), showing underlying potential as a sustainable mining technology.

## EVOLUTION OF REE MINING TECHNOLOGY

IADs are formed by the weathering of bedrock and the accumulation of REEs in weathering crusts, where REEs predominantly adsorb onto clay minerals as trivalent hydrated cations. These REE ions can be readily released by injecting other electrolyte solutions based on the mechanism of ion exchange; thus, REEs are mined by leaching techniques.

To date, three generations of mining technology have been developed for IAD mining; namely, pond leaching, heap leaching, and *in situ* leaching. The pond and heap leaching techniques almost exclusively occur via physical excavation (i.e., the process of physically removing solid ores) and chemical leaching. Such processes destroy the original mountain and generate inexorably large quantities of solid waste, causing permanent damage to the ecosystem. Therefore, pond and heap leaching techniques have been restricted for REE mining.

Currently, *in situ* leaching has become the dominant technique in industrial applications, and nearly all IADs are mined via *in situ* leaching.<sup>1</sup> A high concentration of ammonium salt solutions is poured into the injection wells that are dug *in situ* in the subsurface. The adsorbed REEs are released, transported, and collected at the production well/pool. Compared with previous techniques, the *in situ* leaching technique avoids the physical excavation process and generates less solid waste, reducing the environmental impacts on the topography of the mountain. However, substantial new environmental issues, such as water and soil contamination by ammonia nitrogen, emissions of unexpected harmful elements, and



**Figure 1. Illustration of IAD mining via EKM** The hydrated REEs are expected to be mobilized, transported, and extracted from an IAD under an applied electric field.

landslides, have arisen due to the large quantities of leaching agents used in mining practices. It has been reported that to acquire 1 ton of rare earth oxide (REO), 7–15 tons of ammonium salts must be injected into the soil.<sup>1</sup>

### DEVELOPMENT OF A SUSTAINABLE MINING TECHNOLOGY

To develop a new REE mining technology, mineralogists revisit the metallogenetic mechanism of IADs and the mechanism of REE adsorption onto clay minerals. Recent progress in these mechanistic studies provides opportunities for the development of a new mining technology. Adsorption of REE ions onto clay minerals has been suggested to occur through weak electrostatic interactions. Researchers have suggested that, upon desorption from clay minerals, these REE ions could be mobilized and transported in the weathering crust by an applied force; e.g., an electric field force. Thus, they have proposed the concept of EKM for efficient and sustainable REE recovery.<sup>1</sup>

Electrokinetics involves the application of a direct or alternating electric field to accelerate the migration of movable species, such as metals, water, and particles. The principle of EKM has been suggested to be primarily electromigration and electroosmosis. In an applied voltage gradient, REE fluids, including REE ions and water, are expected to be accelerated, unidirectionally transported from the anode to the cathode, and collected near the cathode (Figure 1).

By replacing the conventional concentration field with an electric field, the quantity of the chemical agents required to activate ions is substantially reduced, significantly lowering the environmental impacts. The REE fluid flow is accelerated by electric fields, remarkably shortening the mining time. Furthermore, the collected amount of REEs has increased due to the unidirectional control of REE fluids by electric fields, thereby preventing the leakage of REE fluids. Unexpectedly, researchers have identified that impurities such as aluminum and calcium are autonomously inhibited in the collected leachates during the electrokinetic process. This helps in the subsequent REE purification and separation. The mechanism is revealed to be the mobility and reactivity diversities between REEs and impurities.

To verify the viability of this EKM technology for REE mining, research teams have carried out experiments at various spatial scales, from gram to kilogram to ton scales. Very recently, it was reported that a demonstration project at the scale of approximately 5,000 tons of weathering crust soils has been built in Meizhou City, China. The results are highly encouraging, as all of the claimed reductions in environmental impacts have been achieved. This further confirms the viability of the approach at an industrial scale.

### MINING TECHNOLOGY INNOVATION WITH ELECTROKINETICS

The use of electrokinetics to mining has attracted extensive attention since being proposed. The strategy could be “a game changer, providing that it is feasible at a large scale,” says Anouk Borst, a geologist at Katholieke Universiteit (KU) Leuven.<sup>2</sup> Henning Prommer, an environmental engineer at the University of Western Australia, points out that “the use of electrokinetics promises a more efficient extraction while substantially reducing environmental impacts.”<sup>3</sup> In addition to REEs, some other researchers have applied EKM to copper.<sup>4</sup> Both laboratory-scale experiments and multiphysics numerical model simulations confirm the applicability of EKM for copper recovery. The successful application of EKM to different metals may lead to mining technology innovation. The EKM has the potential to be a new-generation mining technique for REEs as well as other critical metals, such as copper, carbonate clay-type lithium, laterite nickel, and weathered crust elution-deposited scandium ores. For practical applications, further studies should be focused on the scale effect and engineering problems (i.e., implementation, optimal parameters, and simultaneous control) of EKM due to the existence of multifarious electrodes.

### ELECTROKINETIC MINING CONTRIBUTES TO SUSTAINABLE DEVELOPMENT GOALS (SDGs)

The application of electrokinetics shows great promise for fostering a sustainable future in metal recovery, accompanied by a substantial reduction

of environmental impacts. The mining industry is directly related to all SDGs,<sup>5</sup> and the contribution of the mining industry to each SDG has been explained in detail by Muhammet Devci and coworkers. They have investigated the degree of importance of the 17 SDGs in sustainable mining and suggested that the most and the least important SDGs for sustainable mining were SDG8 (decent work and economic growth) and SDG14 (life below water), respectively. Furthermore, the most important risks for sustainable mining in Greece have been suggested to be directly connected to the aim and scope of SDG12 (responsible consumption and production).

EKM technology can reduce the disposal of polluted water, hazardous gas, and solid waste, which supports the accomplishment of “SDG6 (clean water and sanitation), SDG13 (climate action), and SDG15 (life on land), respectively. Moreover, the mining industry generally uses conventional energy (e.g., coal and oil) and is energy intensive, which is the main contributor to CO<sub>2</sub> emission. Introducing electricity to clean up the mining industry contributes to energy sustainability (i.e., SDG7: affordable and clean energy). In addition, the raw materials for manufacturing various life products are predominantly obtained via mining metals, nonmetals, oil, and gas. “Responsible consumption and production” are the aims of SDG12. The EKM technology requires less leaching agent (consumption) but yields a higher rate and less environmental waste (production). This reduces resource consumption and environmental pollution throughout the full life cycle and promotes a circular economy. Hence, EKM contributes largely to SDGs.

### CONCLUSION

In summary, the innovative EKM opens up a new path for sustainably recovering REEs. The experimental results at different scales suggest that EKM has the potential to be a new-generation mining technique for REEs as well as other critical metals, such as copper, carbonate clay-type lithium, laterite nickel, and weathered crust elution-deposited scandium ores. The development of EKM technology undoubtedly has significant implications for and contributes insights into the current mining technologies, thereby promoting the environmentally friendly utilization of natural resources. Sustainable mining will certainly serve the SDGs for all human beings. Consequently, the application of electrokinetics holds great promise for a sustainable future in metal recovery with a significantly reduced environmental footprint.

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### DECLARATION OF INTERESTS

The authors declare no competing interests.