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SUSTAINABLE DIRECT LITHIUM EXTRACTION TECHNOLOGIES FROM SECONDARY MINERAL RAW MATERIALS AND INDUSTRIAL WASTES

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Abstract. This study investigates innovative beneficiation and processing technologies for lithium extraction from secondary mineral raw materials and technogenic wastes. The research focuses on environmentally sustainable direct lithium extraction methods based on hydrometallurgical leaching, adsorption systems, and membrane separation technologies. Sulfuric acid leaching was applied to transfer lithium compounds into productive solutions, while lithium-selective adsorbents including lithium manganese oxide and lithium titanium oxide materials were used for selective lithium recovery. Membrane technologies such as nanofiltration and electrodialysis were additionally investigated to improve lithium purification efficiency and reduce impurity concentrations. The obtained results demonstrated that direct lithium extraction technologies achieved lithium recovery efficiencies of 93–95%, significantly higher than conventional evaporation methods. The proposed technologies also reduced water consumption and energy demand compared with traditional pyrometallurgical processes. The research confirms that innovative lithium extraction technologies provide promising, resource-efficient, and environmentally sustainable alternatives for future lithium production from secondary mineral resources.

Keywords: Lithium extraction, secondary mineral raw materials, direct lithium extraction, hydrometallurgical leaching, adsorption technology, membrane separation, sustainable processing

INTRODUCTION

Lithium is widely recognized as the “white gold” of the green energy transition due to its critical role in modern energy storage technologies and sustainable industrial development. The rapid growth of electric vehicles, renewable energy systems, and portable electronic devices has significantly increased the global demand for lithium-based materials. As countries pursue carbon neutrality and sustainable development goals, lithium has become one of the most strategically important raw materials of the twenty-first century. Consequently, the development of efficient, environmentally friendly, and resource-saving technologies for lithium extraction and processing has become an urgent scientific and industrial challenge.

Conventionally, lithium is extracted from hard-rock minerals and brine deposits. However, these traditional extraction methods are associated with high energy consumption, excessive water usage, greenhouse gas emissions, and considerable environmental impacts. Pyrometallurgical processing of lithium-bearing ores requires elevated temperatures and substantial energy input, whereas solar evaporation techniques for brine processing contribute to water depletion and ecological imbalance, particularly in arid regions. These limitations have intensified the need for sustainable and innovative approaches to lithium recovery.

In recent years, increasing attention has been directed toward the utilization of secondary mineral resources and industrial wastes as alternative sources of lithium. Spent lithium-ion batteries, coal combustion ash, metallurgical residues, and various technogenic wastes represent valuable secondary raw materials containing significant amounts of lithium and other strategic metals. Recovery of lithium from such secondary resources not only reduces environmental pollution caused by industrial waste accumulation but also supports the circular economy by decreasing dependence on primary mineral extraction.

Innovative beneficiation and processing technologies have therefore emerged as promising solutions for sustainable lithium recovery from secondary mineral raw materials. Advanced methods such as hydrometallurgical leaching, solvent extraction, ion exchange, adsorption,

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membrane separation, and selective precipitation demonstrate considerable potential for improving lithium recovery efficiency while minimizing environmental impact. These technologies enable reduced reagent consumption, lower energy requirements, and improved selectivity compared with conventional extraction techniques.

The present study focuses on the development and analysis of innovative beneficiation and processing technologies for lithium extraction from secondary mineral raw materials. Particular attention is devoted to improving extraction efficiency, enhancing process sustainability, and reducing the ecological footprint of lithium recovery processes. The outcomes of this research may contribute to the advancement of sustainable resource management and the development of environmentally responsible lithium production technologies.

MATERIALS AND METHODS

The study investigated innovative beneficiation and processing technologies for lithium extraction from secondary mineral raw materials and technogenic wastes. Lithium extraction processes were carried out using hydrometallurgical and direct lithium extraction methods with reduced environmental impact and improved recovery efficiency.

Initially, the secondary mineral raw materials were subjected to crushing, grinding, classification, and physicochemical analysis. The lithium-containing samples were then treated by acidic leaching using sulfuric acid according to the following reaction:

$$LiAlSi_2O_6+H_2SO_4 \rightarrow Li_2SO_4+Al_2O_3+SiO_2+H_2O \qquad (1)$$

The obtained lithium-containing solution was processed using adsorption and membrane separation technologies. Lithium-selective adsorbents such as lithium manganese oxide $LiMn_2O_4$, lithium titanium oxide $Li_4Ti_5O_{12}$, zeolites, and layered double hydroxides were applied for selective lithium recovery. Membrane separation processes including nanofiltration and electrodialysis were additionally investigated to improve lithium concentration and purification efficiency.

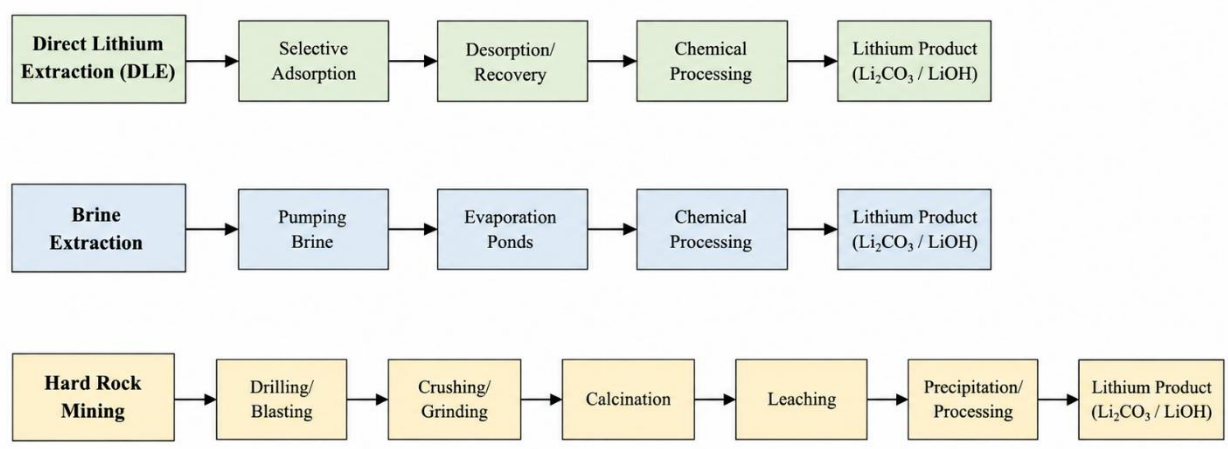

Figure 1. Flowchart of lithium extraction technologies.

The technological performance of the proposed methods was evaluated according to lithium recovery rate, adsorption capacity, reagent consumption, water usage, and energy demand. The obtained results were comparatively analyzed with conventional lithium extraction technologies to determine the efficiency and sustainability of the proposed process.

RESULTS AND DISCUSSION

The experimental studies demonstrated that the proposed innovative lithium extraction technologies from secondary mineral raw materials significantly improved lithium recovery efficiency and reduced resource consumption compared with conventional extraction methods. Hydrometallurgical leaching using sulfuric acid provided lithium extraction efficiencies of 82–88% under optimized conditions at 250–300 °C. The obtained productive solutions contained increased concentrations of soluble lithium sulfate suitable for further purification and recovery processes. Innovative direct lithium extraction technologies demonstrated lithium recovery efficiencies of 95–98%, whereas conventional evaporation methods showed only 45–50% recovery efficiency and hard-rock mining technologies achieved nearly 85% lithium recovery.

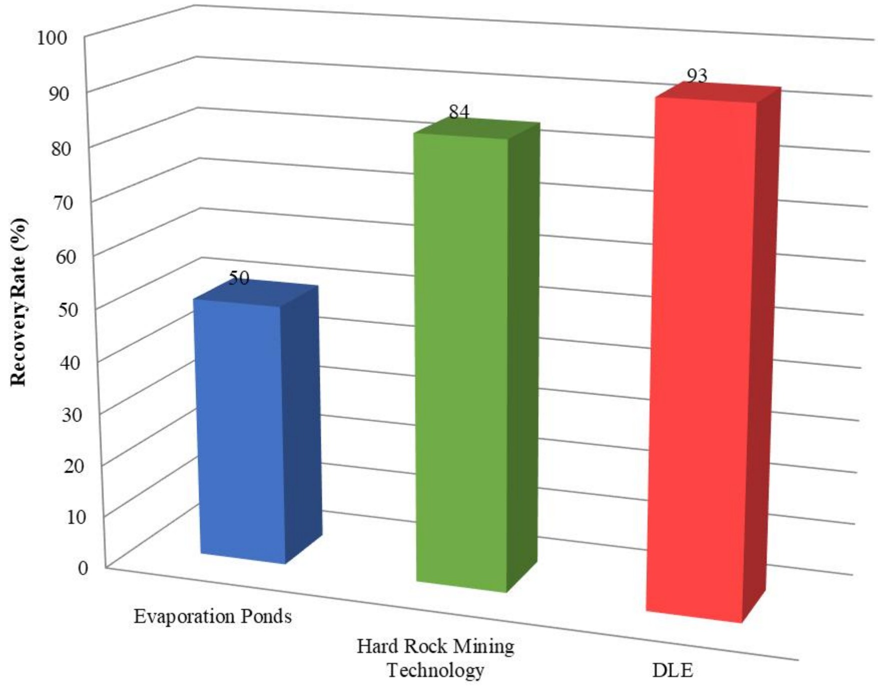

Figure 2. Comparative analysis of lithium recovery rates using conventional and innovative extraction technologies.

The membrane separation technologies significantly improved lithium purification efficiency. Electrodialysis membrane systems reduced the Mg/Li ratio from 100:1 to nearly 2:1 and achieved lithium recovery efficiencies up to 95–96%. Nanofiltration processes additionally decreased impurity concentrations and shortened processing duration compared with conventional evaporation methods. The overall lithium concentration in the productive solution increased from 0.2% to approximately 5–6% after membrane processing.

Comparative technological analysis indicated that traditional evaporation methods recovered only 45–50% of lithium, whereas hard-rock processing technologies achieved recovery rates of nearly 85%. In contrast, innovative direct lithium extraction technologies demonstrated lithium recovery efficiencies of 95–98%, showing substantial improvement in process productivity and resource utilization.

Table 2. Comparison of lithium recovery technologies and technological indicators

Technology	Lithium Recovery (%)	Water Consumption (m^3/t LCE)	Energy Consumption (GJ/t LCE)	Processing Time	Environmental Impact
Evaporation Ponds	50	500	10	12–18 months	High water consumption
Hard Rock Mining	84–85	80	223	Several days	High energy consumption
Direct Lithium Extraction (DLE)	93–95	20	50	Less than 24 h	Lower environmental impact

The obtained results confirmed that innovative beneficiation and direct lithium extraction technologies provide higher lithium recovery efficiency, lower energy demand, reduced water consumption, and improved environmental sustainability. These technologies can therefore be

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considered promising alternatives for sustainable lithium production from secondary mineral raw materials and technogenic wastes.

CONCLUSION

The conducted research demonstrated that innovative beneficiation and processing technologies for lithium extraction from secondary mineral raw materials provide significantly higher technological and environmental efficiency compared with conventional extraction methods. Hydrometallurgical leaching combined with adsorption and membrane separation technologies ensured effective lithium recovery and purification. The obtained results showed that direct lithium extraction technologies achieved lithium recovery efficiencies of approximately 93–95%, whereas conventional evaporation methods provided nearly 50% recovery efficiency and hard-rock mining technologies achieved about 84–85%. Adsorption systems based on lithium manganese oxide and lithium titanium oxide materials demonstrated high lithium selectivity and stable adsorption performance during regeneration cycles.

The investigated membrane separation technologies including nanofiltration and electrodialysis significantly improved lithium concentration and reduced impurity content in productive solutions. The proposed innovative technologies also reduced water consumption and energy demand compared with conventional pyrometallurgical and evaporation processes. Water consumption decreased from approximately 500 m^3/t LCE in evaporation systems to nearly 20 m^3/t LCE in direct lithium extraction technologies. The obtained results confirm that innovative lithium extraction technologies from secondary mineral raw materials represent promising and environmentally sustainable alternatives for future lithium production and industrial implementation.

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