Optimization of operational parameters in the production of lithium carbonate from lepidolite: systematic review

Optimización de parámetros operacionales en la obtención de carbonato de litio a partir de lepidolita: revisión sistemática

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REVISTA INVECOM ISSN: 2739-0063

Received: 26-02-2025 Accepted: 20-05-2025

2026. V6. N1.

Abstract

The growing demand of emerging technological sectors, such as the manufacture of batteries for electric vehicles, electronic devices and clean energy storage systems, makes hydrometallurgical leaching an economically viable and environmentally safe technical option as long as the operating conditions are carefully controlled. Therefore, the present study was carried out by gathering scientific articles published in the last decade on three key variables of the hydrometallurgical process: temperature, reagent concentration and leaching time. This was carried out by means of a systematic review based on the PRISMA protocol, through which 43 relevant articles were selected for analysis. The data analyzed confirm that the three parameters mentioned above directly affect lithium recovery efficiency and that tighter control of parameters can make lithium recovery more effective and sustainable. The paper also investigates emerging technologies such as real-time monitoring systems as habits to improve performance and reduce environmental impact. The contribution of this review is to offer a critical and updated view of the subject, providing a useful basis for improving lepidolite hydrometallurgy and thereby establishing a more sustainable lithium industry.

Keywords: leaching, hydrometallurgical processes, lithium minerals.

Resumen

La creciente demanda de sectores tecnológicos emergentes, como la fabricación de baterías para vehículos eléctricos, dispositivos electrónicos y sistemas de almacenamiento de energía limpia, convierte a la lixiviación hidrometalúrgica una opción técnica económicamente viable y ambientalmente segura en la medida en que las condiciones operacionales son controladas con riguroso cuidado. Por ende, se realizó el presente estudio que reúne artículos científicos publicados en la última década acerca de tres variables clave del proceso hidrometalúrgico: temperatura, concentración de reactivos y tiempo de lixiviación. Todo ello se llevó a cabo mediante una revisión sistemática basada en el protocolo PRISMA, a través del cual se seleccionaron 43 artículos relevantes para el análisis. Los datos analizados confirman que los tres parámetros mencionados anteriormente afectan directamente la eficacia de recuperación del litio y que un control más estricto de parámetros puede hacer que la recuperación de litio sea más efectiva y sostenible. El trabajo también investiga tecnologías emergentes como sistemas de monitoreo en tiempo real como hábitos para mejorar el rendimiento y reducir el impacto ambiental. La contribución de esta revisión es ofrecer una visión crítica y actualizada del tema, brindando una base útil para mejorar la hidrometalurgia de lepidolita y, por lo tanto, establece una industria de litio más sostenible.

Palabras clave: lixiviación, procesos hidrometalúrgicos, minerales de litio.

Introduction

Lithium has become a central element in the energy transition. Today, it powers batteries that drive electric vehicles, fuel phones, and store energy generated from solar and wind sources (IEA, 2022; Yan et al., 2023). Its value is no longer measured solely in economic terms but also by its ability to support a more sustainable energy model. Consequently, many countries have prioritized its production and refinement within their technological and environmental development agendas (USGS, 2023; Giordano & Díaz, 2020).

In this context, scientific and industrial research has focused on alternative sources of lithium that are viable both economically and environmentally. Among these, lepidolite stands out as a lithium-rich phyllosilicate mineral with physicochemical properties that facilitate its industrial processing (Vieceli et al., 2017; Korbel et al., 2023). Acid leaching has proven to be a promising option due to its energy efficiency, good selectivity, and low environmental impact (Rosales et al., 2022; Peyré & Dorn, 2020).

The efficiency of this hydrometallurgical process largely depends on the proper optimization of operational parameters, particularly temperature, reagent concentration, and leaching time. These factors directly influence lithium recovery, product purity, and process profitability (Rosales et al., 2023; Choi & Wang, 2020). Recent studies indicate that precise control of these variables not only improves technical performance but also enhances the overall sustainability of the system (Liu & Azimi, 2021; Wu et al., 2022).

For instance, a moderate increase in temperature accelerates the dissolution kinetics without compromising selectivity (Mendieta-George et al., 2021; Wu et al., 2022). Maintaining appropriate reagent concentrations maximizes recovery while minimizing the dissolution of impurities such as iron or aluminum (Luo et al., 2023). Regarding leaching time, excessive duration increases costs without providing proportional improvements in yield (Mulwanda et al., 2021). These elements underscore the necessity of adopting a comprehensive approach that considers both individual effects and synergies among variables (Jung et al., 2021).

This study aims to analyze scientific articles published between 2014 and 2024 that address the influence of operational parameters on lepidolite leaching. Patterns, recurring methodologies, and relevant knowledge gaps will be identified, and the industrial applications of these findings will be discussed, with the goal of strengthening a more competitive, efficient, and sustainability-aligned lithium value chain.

Methodology

This study is framed within a systematic literature review developed from a qualitative and exploratory approach, following the guidelines of the PRISMA model (Moher et al., 2009). The objective was to identify and analyze research focused on the optimization of operational parameters in the extraction of lithium carbonate from lepidolite via hydrometallurgical leaching. Experimental studies published in indexed scientific journals were prioritized, particularly those addressing three key dimensions: technical process performance, environmental viability, and industrial applicability.

The bibliographic search was conducted in the Scopus and Web of Science databases, selected for their extensive coverage in the fields of chemical engineering, extractive metallurgy, and materials science (Vieceli et al., 2017). To narrow results and improve search accuracy, combinations of key terms in English such as “lithium extraction, lepidolite, hydrometallurgical leaching, operational parameters, and process optimization” were employed, connected by Boolean operators (AND, OR) (Sánchez Núñez, 2021).

The search focused on studies published between 2014 and 2024, ranging from foundational research to recent works incorporating emerging technologies and innovative approaches for process optimization.

Table 1

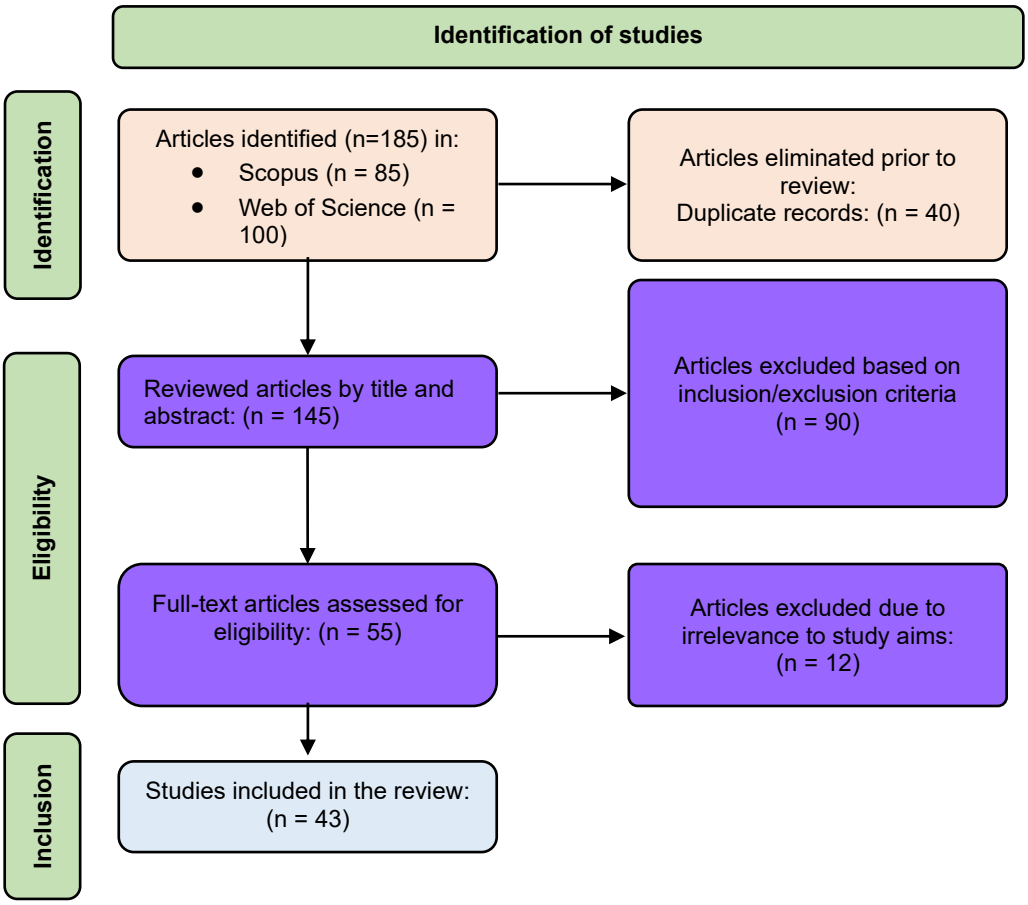
Inclusion and exclusion criteria applied in the systematic review

Inclusion Criteria	Exclusion Criteria
• Studies published in peer-reviewed scientific journals. • Studies with experimental methodology focused on lepidolite leaching. • Evaluation of operational parameters: temperature, reagent concentration, or leaching time. • Availability of full text in English or Spanish.	• Articles that are exclusively theoretical or simulation-based without experimental validation. • Studies focused on minerals other than lepidolite (e.g., spodumene, zinnwaldite). • Duplicated documents or those with significant methodological deficiencies.

Ultimately, 43 studies meeting all criteria were selected, incorporated into the systematic analysis, and organized in a comparative matrix. To ensure the quality of the evidence analyzed, a critical assessment was applied based on the guidelines of the Joanna Briggs Institute (JBI, 2021). Priority was given to those works presenting solid experimental design, methodological reproducibility, and clear statistical underpinning.

The data extracted from the selected studies were systematized according to the type of evaluated parameter (temperature, reagent concentration, or leaching time), enabling comparison of experimental approaches, identification of recurring patterns, and recognition of significant methodological divergences that contribute to the comprehensive analysis of the process.

Figure 1
PRISMA method diagram



Results and discussion

The reviewed studies confirm that temperature, reagent concentration, and leaching time are the most determining operational factors in the efficiency of lithium carbonate extraction from lepidolite. Strategic adjustment of these variables not only enhances metal recovery but also increases economic efficiency and reduces the environmental impact of the system.

Lepidolite and its properties

Lepidolite is a silicate mineral from the phyllosilicate group characterized by its high lithium content, positioning it as a strategic raw material in lithium extraction processes (López et al., 2024). Its chemical composition includes lithium, aluminum, silicon, and potassium, along with trace amounts of rubidium and cesium, elements that endow it with differentiated properties compared to other silicates (Korbel et al., 2023).

Structurally, it consists of alternating layers of silicate tetrahedra and metallic ions such as lithium, configuring a layered structure typical of mica-type minerals. This characteristic grants lepidolite excellent exfoliation, facilitating its division into thin sheets (Zarza-Díaz, 2024). According to Meshram et al. (2021), this property allows for greater surface exposure of the mineral during leaching, favoring the dissolution efficiency of lithium.

Additional important properties of lepidolite include its coloration, which ranges from pink to gray, and its low hardness (2.5 to 3 on the Mohs scale), making it particularly suitable for milling operations and hydrometallurgical processing (Rosales et al., 2017). These characteristics, along with its ability for laminar separation, explain its favorable behavior in treatments with acidic leachants.

In industrial terms, lepidolite presents itself as a viable alternative source of lithium, especially due to its availability and favorable response in extraction processes under moderate conditions (Peyré & Dorn, 2020). Recent research has also evaluated its behavior against alternative leachants, such as organic acids, which reduce the aggressiveness of the medium without compromising recovery efficiency (Ibrahim et al., 2022). However, its utilization largely depends on the operational design of the process, reinforcing the importance of understanding its structure and reactivity with different leaching agents (Vieceli et al., 2017).

Figure 2
Chemical composition of lepidolite



Note. obtained from Valderrey, 2020

Hydrometallurgy in lithium extraction

Hydrometallurgy is a widely employed technique for metal extraction using aqueous solutions and has proven effective for recovering lithium contained in minerals such as lepidolite. This process encompasses stages of crushing and milling the mineral, which liberates the lithium contained in its crystalline structure, followed by an acid leaching stage where reagents like sulfuric or hydrochloric acid are used to dissolve lithium compounds and separate them from other mineral phases (Marcinov et al., 2023).

Compared to pyrometallurgical processes, hydrometallurgy operates at lower temperatures, significantly reducing energy requirements. Additionally, it offers greater control over chemical reactions, allowing for the production of high-purity lithium solutions, a fundamental attribute for advanced electrochemical applications, particularly in the production of high-energy-density lithium-ion batteries (Vieceli et al., 2017). Recent studies, such as that by Lee (2021), explore alternative technologies to solar evaporation for concentrating lithium in intermediate solutions.

However, the hydrometallurgical treatment of lepidolite poses significant operational challenges. This mineral is often found associated with other metallic elements, necessitating careful adjustment of parameters such as reagent concentration, pH, and leaching time to avoid the dissolution of impurities or lithium losses. As a technical alternative, Vieceli et al. (2018) demonstrated that mechanical activation combined with acid digestion improves lithium extraction from lepidolite under mild conditions.

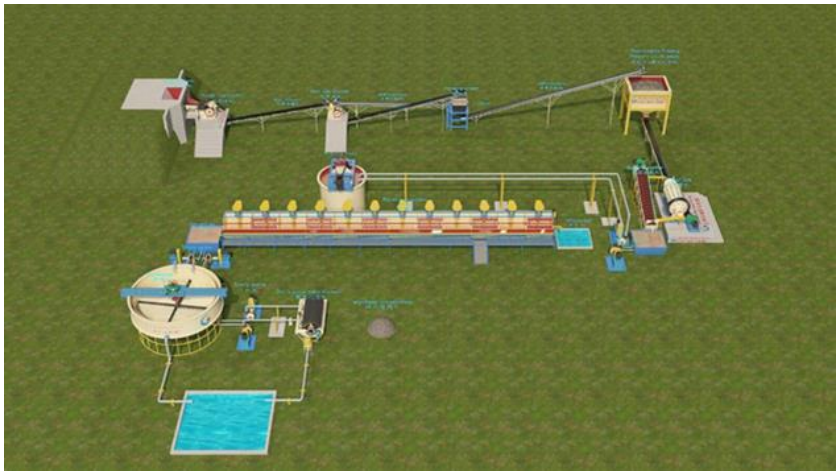
Furthermore, the process generates acidic liquid waste and potentially toxic by-products, whose inadequate treatment poses a risk of soil and water contamination, affecting process sustainability (Lende, 2022). Concurrently, the use of online sensors and artificial intelligence techniques has been explored as a means to dynamically adjust operational conditions, enabling more precise real-time system control (Nguyen et al., 2021).

From an economic perspective, the intensive use of reagents and waste management are determining factors that can significantly increase process costs. Thus, various recent studies have highlighted the need to optimize leaching conditions, incorporating technological strategies aimed at chemical efficiency and minimizing secondary waste (Cerrillo-Gonzalez et al., 2020).

In this context, the reviewed studies agree that hydrometallurgy applied to lepidolite constitutes a promising pathway for lithium compound production, but its efficiency and sustainability critically depend on the design and control of operational parameters. Nonetheless, pilot-scale studies have shown that optimal laboratory-

defined conditions do not always translate into the same industrial yield, necessitating technical redesign at larger scales (Park et al., 2023).

Figure 3
Hydrometallurgical process applied to lepidolite



Note. obtained from JXSC, 2020

Key factors in the leaching process

The analyzed studies concur that the efficiency of the lepidolite leaching process fundamentally depends on the adjustment of three operational variables: temperature, reagent concentration, and contact time. These variables do not act in isolation but are deeply interrelated, and their combination determines both the effective recovery of lithium and the associated costs and environmental impact of the process (Calizaya, 2022; Jung et al., 2021).

First, temperature directly influences the dissolution kinetics of lithium, accelerating chemical reactions as it increases. However, excessive values raise energy consumption and may induce the dissolution of unwanted impurities, such as iron or aluminum, complicating subsequent product purification (Wu et al., 2022). For this reason, the literature suggests operating within an optimal thermal range that maximizes recovery without compromising process selectivity.

Regarding reagent concentration, particularly of acids such as H_2SO_4 or HCl, intermediate levels have been documented to favor the breakdown of the crystalline structure of lepidolite, facilitating lithium release. However, high concentrations can lead to secondary reactions, increase equipment corrosion, and elevate operational costs. Conversely, concentrations that are too low reduce overall process efficiency by limiting the availability of reactive species (Luo et al., 2023).

Leaching time also represents a critical parameter that directly influences yield. Insufficient times may result in incomplete dissolutions, while prolonged times increase energy costs and mechanical wear on equipment without providing proportional benefits (Calizaya, 2022). Therefore, it is recommended to establish a balance that maximizes recovery without incurring operational penalties.

An increase in temperature could reduce both contact time and the necessary acid concentration without significantly affecting extraction efficiency (Jung et al., 2021). This synergy should be addressed through comprehensive optimization strategies, such as experimental design or multivariable modeling. The use of statistical methods like Response Surface Methodology (RSM) has proven effective in finding optimal combinations of operational variables, enhancing recovery without the need for multiple experimental trials (Chen et al., 2021). Rosales et al. (2022), working with mechanically activated α-spodumene mixtures, applied RSM to optimize leaching parameters, confirming its effectiveness even in low-grade minerals.

Consequently, proper management of these parameters not only improves lithium recovery and the quality of the final product but also contributes to resource use efficiency, waste reduction, and the economic competitiveness of the process. These findings are particularly relevant in a context where industrial pressure for

sustainability and operational performance is increasingly significant (Wu et al., 2022). In this regard, Choi (2020) demonstrated that a carbonation stage following leaching can significantly enhance the quality of the lithium carbonate obtained.

Influence of temperature on process efficiency

Temperature plays a crucial role in the rate of chemical reactions involved in lithium dissolution. Reviewed studies highlight that an increase in temperature accelerates the kinetics of the process, favoring the recovery rate (Wu et al., 2022). However, excessively high values are not always sustainable from an energy perspective and may induce the release of impurities such as iron or aluminum, complicating the purification stage (Sánchez Núñez, 2021). Various authors agree that an optimal temperature range should be established, tailored to the characteristics of the mineral being treated, to achieve a balance between efficiency, product purity, and energy consumption (Mendieta-George et al., 2021). In this sense, temperatures between 80 °C and 100 °C have been identified as effective for balancing recovery efficiency and energy consumption, particularly in industrial settings (Tadesse & Lee, 2020).

Reagent concentration and selectivity control

Regarding reagent concentration, particularly acids like H_2SO_4, analyzed works indicate that there is a chemical threshold beyond which no significant improvements are achieved, and negative effects such as the dissolution of unwanted elements or medium saturation may occur (Luo et al., 2023). Most studies employ concentrations between 2 and 4 mol/L, which have shown favorable results in terms of recovery and process control. However, it is advisable to avoid overuse of reagents, as this increases costs and the environmental burden of the system (Liu & Azimi, 2021). This balance should be reached by carefully adjusting the amount of reagents based on operational conditions and the type of lepidolite processed. Additionally, life cycle analysis (LCA) studies have shown that excessive use of acids significantly increases the environmental footprint of the process, reinforcing the need for strict control of these parameters (García et al., 2022).

Leaching time and industrial yield

Concerning leaching time, literature agrees that a period between 1 and 3 hours allows for good lithium recovery, provided that controlled temperature and agitation conditions are maintained. Too short times may lead to incomplete processes, while prolonged periods increase equipment wear and operational costs without providing proportional benefits (Calizaya, 2022). Thus, a case-by-case evaluation is suggested, adapting contact time to the mineral's granulometry, the concentration of the leachant, and the applied temperature.

Relationship and interdependence among parameters

One of the most relevant findings of this review is that the three operational factors do not act in isolation but are deeply interrelated. For example, an increase in temperature can shorten the required leaching time, or a higher concentration of reagents can compensate for a lower temperature. This interaction requires an integrated approach that allows for the simultaneous optimization of parameters (Jung et al., 2021). In this regard, simulation models and methodologies based on experimental design have proven useful tools for finding efficient combinations. Additionally, multivariable optimization models have been proposed to evaluate temperature, concentration, and time simultaneously, identifying highly efficient combinations (Singh & Patel, 2023).

Operational limitations and challenges in industrial scale

Despite advances in optimizing parameters, significant limitations exist when scaling processes from the laboratory to industrial levels. One of the main challenges is the compositional variability of lepidolite across different deposits, which affects the reproducibility of experimental results (López et al., 2024; Meshram et al., 2021). Additionally, factors such as mineral granulometry and the presence of impurities interfere with the efficiency of the leachant, causing unexpected deviations in lithium recovery (Rosales et al., 2017; Marcinov et al., 2023).

Other authors warn that costs associated with liquid waste management and equipment corrosion can compromise the economic viability of the process if not adequately controlled (Cerrillo-Gonzalez et al., 2020; Lende, 2022; Díaz, 2020). Economically, studies like that of Quispe López (2020) propose costing models to optimize production in operational contexts with input limitations. In this scenario, it becomes crucial to adopt an

integrated approach that considers not only chemical parameters but also mechanical, energy, and environmental aspects.

Complementary research, such as that by Mulwanda et al. (2021) and Mendieta-George et al. (2021), has highlighted the need to experimentally validate optimization models under real plant conditions. These studies emphasize that many proposals, while promising in the lab, require technological adaptation before large-scale implementation.

Industrial application of optimization

At the industrial level, several documented case studies in the literature report significant improvements in recovery efficiency and the quality of lithium carbonate obtained when operational optimization strategies were applied. These improvements include a reduction in the use of chemical reagents, lower energy consumption, and decreased total processing time (Cid & Sebastián, 2024).

From a broader perspective, this industrial vision aligns with a comprehensive outlook on lithium as a strategic resource in the sustainable development of Latin America (Giordano & Díaz, 2020). Moreover, recent research incorporates artificial intelligence techniques and real-time control systems, allowing for adjustments in operating conditions based on variations in feed or process requirements (Rosales et al., 2021; Villa Canaviri, 2023). Serrano & Soto (2022) emphasize the importance of integrating hybrid energy and cooling systems in high-thermal-demand industrial processes such as lithium extraction.

In summary, the efficiency of the hydrometallurgical process for obtaining lithium carbonate from lepidolite can be significantly improved by properly adjusting the key operational factors in conjunction. This is not merely a technical or economic improvement but also a genuine opportunity to advance towards a cleaner production method with a lower environmental impact.

Conclusions

The systematic review clearly defined that the effectiveness of the hydrometallurgical process for lithium carbonate extraction from lepidolite depends on the combined action of three operational parameters: temperature, reagent concentration, and leaching time. The accumulated information shows that there is no singular, universally optimal value for each variable; rather, their behavior must be examined considering the physicochemical properties of the mineral being treated and the type of leachant used.

Furthermore, the findings demonstrate that the traditional approach based on sequential adjustments has long been replaced by integrated optimization strategies, many of which are based on emerging technologies. The establishment of real-time control systems, predictive algorithms, and models based on artificial intelligence is beginning to revolutionize industrial environments dedicated to lithium processing. These tools, far from being optional, are emerging as structural mechanisms to increase operational efficiency, minimize energy consumption, and improve process traceability in the face of increasingly stringent environmental demands.

From an environmental framework, it was found that the global control of operational parameters not only maximizes technical performance efficiency but also directly influences the minimization of waste and emissions. This review also uncovers a set of critical research gaps for the development of the sector, highlighting the urgent need to validate, at pilot or industrial levels, combinations of operational parameters that have already shown promising results under laboratory conditions. Additionally, there is a need to design less aggressive reagents with lower environmental impact, as well as to integrate adaptive systems capable of responding to dynamic changes in mineral composition or operational variations. Together, this work offers a robust technical and conceptual framework that can guide researchers, engineers, and plant managers in designing more efficient processes that align with the contemporary challenges of the lithium industry.

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