

Optimization of processing costs could improve the cost-competitiveness of lithium extraction from clay relative to conventional sources of brines and hard rock ores

Corresponding Author: Dr Andrew Haddad

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The topic presented in the manuscript show novelty, as economic evaluation regarding clay-based lithium extraction and production has not been widely published so far. I believe the research paper will give valuable information for decision makers and the field in general. The manuscript is well written and does not seem to contain many flaws. There are only a few points I would like to make:

1) In comparing the brine- and hard rock-based lithium production, is the comparison really made between lithium products, or are the hard rock processes actually producing spodumene concentrate? This would not be a fair comparison, as the concentrate needs further processing, with similar chemical and general even higher energy requirements as the brine-based processing. I believe the source the authors have used (S&P Global Market Intelligence (Ref. 28)), is reporting only concentrate beneficiation costs, not including lithium refining that would follow. The authors should make it clear (for example when discussing Figure 1) if they have done comparison between brine-based lithium chloride/carbonate and hard rock-based mineral concentrate, or have they actually compared similar level lithium products. For reference, the authors should review, e.g. <https://doi.org/10.1016/j.clet.2024.100749> and <https://doi.org/10.31035/cg2022088>.

2) On page 8, line 215, the authors are talking about sulfur as a reagent. It should be clarified that is the sulfur used in sulfuric acid production or somewhere else.

3) The Methods section should come before Results.

Reviewer #2

(Remarks to the Author)

Thanks for the revised manuscript. The effort to compile project-level data for lithium extraction from clay is appreciated. However, after carefully reviewing the revised version, I still have several fundamental concerns.

First, the manuscript remains largely a techno-economic cost analysis, with the main focus on processing costs and optimisation pathways. While this is valuable from an engineering or industry perspective, it does not sufficiently align with the scope of Nature Communications Earth & Environment, which requires a clear contribution to environmental science, Earth systems, or sustainability at a deeper level. The environmental aspects (energy, water, emissions) are presented only as supporting metrics and are not analysed in a comprehensive or mechanistic way.

Second, the novelty of the study is limited. The work primarily aggregates publicly available data (feasibility studies and technical reports) and applies standard cost breakdown and sensitivity analysis. There is no clear methodological advancement or new framework that significantly moves beyond existing techno-economic assessments.

Third, the study relies heavily on company-reported data, which are inherently uncertain and often optimistic. The manuscript does not adequately address this limitation, and there is no robust treatment of uncertainty (probabilistic analysis), which is critical given the variability in lithium markets and project assumptions.

In addition, the conclusions appear somewhat speculative, particularly regarding the potential cost reductions (up to 50%) required to achieve competitiveness. These improvements are not demonstrated through validated technological pathways or real operational data.

Importantly, even from an economic perspective, the central claim of the manuscript (suggested already in the title) that optimisation can make clay-based lithium extraction competitive with conventional sources does not fully reflect the current market reality. Recent developments in the lithium industry show that even well-established conventional operations are facing significant economic challenges. For example, in Australia, which is one of the largest producers of spodumene concentrate, there have been major setbacks including the closure of the Albemarle lithium hydroxide plant, the cancellation of expansion plans at Tianqi's Kwinana refinery, and delays in commissioning of the Covalent lithium project. These examples indicate that even mature and relatively lower-cost lithium supply chains are currently under pressure. In this context, the assumption that more complex and less mature clay-based extraction routes can become competitive through cost optimisation alone appears overly optimistic and insufficiently supported.

Finally, the geographical and project scope is limited, with most case studies concentrated in a specific region (primarily Nevada), yet the conclusions are extended to global lithium supply considerations.

Reviewer #3

(Remarks to the Author)

The manuscript presents a solid, well-structured study of high relevance to the field of lithium processing. The analysis is clear and consistent, systematically addressing the economic feasibility of lithium extraction from clays, which is particularly timely given the current growing demand for this resource. The quality of the figures and graphs is especially noteworthy, as they are clear, informative, and facilitate the interpretation of the results as well as the comparison between the evaluated technologies. Furthermore, the level of detail in the study allows for an adequate identification of the main factors influencing process costs.

Nevertheless, several aspects could be improved, as detailed below:

1. It is recommended to further elaborate on the justification of the main model assumptions, particularly those related to reagent consumption and process efficiencies. While lines 487–507 describe the use of data from industrial reports, and lines 561–566 mention the estimation of missing data through process parameters, the criteria used for these approximations are not described with sufficient clarity. Considering that these assumptions have a significant impact on the final cost estimates, greater transparency in their definition would strengthen the robustness and reliability of the analysis presented.

2. It is suggested to deepen the analysis of the leaching process, as it constitutes a key stage in both reagent consumption and operational costs. Although the evaluated technologies are introduced in lines 84–92 and their costs are compared in lines 270–300, the discussion could be expanded to include how operational variables influence these results. In particular, it would be valuable to complement these sections by incorporating the effects of parameters such as pH, temperature, and reagent concentration, as these can affect both extraction efficiency and lixiviant consumption, thereby directly impacting process costs.

3. It is recommended to expand the discussion in the final section (lines 600–650) by incorporating references to emerging leaching approaches that consider both economic and environmental aspects. In this context, the use of alternative complexing agents, such as glycine, has been explored in recent studies, showing promising results in terms of selectivity and potential reduction in reagent consumption. Although its application has been more widely studied in copper recovery, it has also been proposed for use in lithium-bearing systems, representing an interesting direction for future research. Including these perspectives would enrich the manuscript and provide a more up-to-date view of developments in hydrometallurgical technologies (DOI: 10.3389/fceng.2025.1613424; DOI: 10.3390/met16030248).

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have sufficiently answered the comments, and no further clarifications are required. The work is topical and of high quality, and I recommend the publication of this article.

Reviewer #2

(Remarks to the Author)

I appreciate the substantial effort invested in revising the manuscript and preparing the detailed rebuttal. The revised version improves the clarity of the benchmarking methodology, particularly regarding the integrated hard-rock cost comparison, and provides a more detailed explanation of sensitivity analysis assumptions and reagent-related cost drivers. The additional discussion connecting clay-based lithium extraction to sustainability and environmental constraints also improves the contextual framing of the study.

However, after carefully reviewing the revised manuscript, I still have several fundamental concerns.

First, despite the expanded framing, the manuscript remains primarily a techno-economic cost assessment focused on processing costs, benchmarking, and optimisation pathways. The environmental dimensions (water, energy, emissions, and land disturbance) are discussed mainly at a contextual level and are not analysed in a mechanistic or integrated way. As a result, the work still reads more as an engineering and industrial cost-analysis study than as a contribution centred on Earth and environmental systems.

Second, although the authors argue for methodological novelty, the core framework remains based on aggregation and harmonisation of publicly available technical reports combined with conventional cost-breakdown and sensitivity analyses. The additional scenario and isoline analyses improve the presentation of the results but do not fundamentally alter the methodological contribution of the study.

Third, the manuscript still relies heavily on company-reported feasibility data, which are inherently uncertain and often optimistic for pre-commercial projects. While the expanded sensitivity analysis is useful, it does not fully substitute for probabilistic uncertainty treatment or validation against operational performance data.

In addition, despite the revised environmental framing, the manuscript still lacks sufficiently comprehensive engagement with the growing body of recent LCA and sustainability literature related to lithium clay resources and unconventional lithium extraction systems. Several recent studies have already investigated broader environmental trade-offs and sustainability implications associated with lithium clay development, yet these perspectives remain only marginally integrated into the present analysis (like doi.org/10.1016/j.jclepro.2024.142955 which compared salt roasting and acid leaching in Thacker Pass and Sonora Projects, there are also other LCA of Li Clay resources worth checking). Consequently, the environmental relevance of the manuscript remains largely contextual rather than analytically embedded within the study framework.

Finally, the conclusions regarding the future competitiveness of clay-based lithium extraction remain somewhat speculative. The manuscript identifies possible optimisation pathways, but these pathways are not demonstrated at a commercial scale and remain dependent on assumptions regarding technological advances, reagent recovery efficiencies, and future process integration. Importantly, even conventional lithium supply chains are currently facing significant economic and operational challenges under present market conditions. In this context, the conclusion that clay-based extraction routes can become broadly competitive through optimisation alone still appears insufficiently supported.

Overall, the revised manuscript is clearer and more detailed than the previous version. Nevertheless, I do not believe the revisions fundamentally resolve the conceptual and scope-related concerns raised previously.

Reviewer #3

(Remarks to the Author)

I thank the authors for their comprehensive and carefully prepared responses to the reviewer comments. The clarifications provided regarding the methodological assumptions, reagent consumption estimations, and process efficiency criteria significantly improve the transparency and robustness of the study. In addition, the expanded discussion on operational parameters influencing leaching performance, together with the incorporation of emerging hydrometallurgical approaches, further strengthens the scientific relevance and completeness of the manuscript. Overall, the authors have satisfactorily addressed the concerns raised, and the revised version represents a valuable contribution to the field of lithium processing and extraction technologies.

From my side, I have no further comments or additional corrections regarding the revised manuscript.

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Response to reviewers' comments for:

Optimization of processing costs can make lithium extraction from clay competitive to conventional sources of brines and hard rock ores

Communications Earth & Environment

We would like to thank the Editor and the Reviewers for taking the time to review our manuscript and for providing constructive comments and suggestions that have greatly helped us further improving the paper. In the following we respond point-by-point to the comments and suggestions provided.

REVIEWER #1:

The topic presented in the manuscript show novelty, as economic evaluation regarding clay-based lithium extraction and production has not been widely published so far. I believe the research paper will give valuable information for decision makers and the field in general. The manuscript is well written and does not seem to contain many flaws. There are only a few points I would like to make:

We thank Reviewer #1 for the positive assessment of our work and for the constructive suggestions, which have helped us clarify several important points. Our responses to each comment are provided below.

Comments:

1. In comparing the brine- and hard rock-based lithium production, is the comparison really made between lithium products, or are the hard rock processes actually producing spodumene concentrate? This would not be a fair comparison, as the concentrate needs further processing, with similar chemical and generall even higher energy requirements as the brine-based processing. I believe the source the authors have used (S&P Global Market Intelligence (Ref. 28)), is reporting only concentrate beneficiation costs, not including lithium refining that would follow. The authors should make it clear (for example when discussing Figure 1) if they have done comparison between brine-based lithium chloride/carbonate and hard rock-based mineral concentrate, or have they actually compared similar level lithium products. For reference, the authors should review, e.g. <https://doi.org/10.1016/j.clet.2024.100749> and <https://doi.org/10.31035/cq2022088>.

Response: We thank the reviewer for raising this important point and agree that the comparison basis warrants explicit clarification in the manuscript. The reviewer is correct that the headline S&P Global Market Intelligence figure commonly cited for hard rock lithium production (approximately 2,540 USD/t LCE in 2019) reflects spodumene concentrate costs only and is not directly comparable to the refined lithium carbonate and hydroxide costs reported for brine operations and for the clay projects analyzed in this study.

We agree this asymmetry would undermine the fairness of the benchmarking if left uncorrected. For this reason, the hard rock benchmark of 4,996 USD/t LCE used throughout our manuscript is not the S&P concentrate cost alone but already incorporates the additional cost of converting spodumene concentrate to battery-grade lithium hydroxide: it is the sum of the S&P Global concentrate-stage production cost (2,540 USD/t LCE) and the widely cited Greenbushes/Kwinana conversion cost (2,456 USD/t LCE), both reported by S&P Global Market Intelligence (2019).

The benchmark therefore represents integrated hard rock production through battery-grade lithium hydroxide and is on a like-for-like refined-product basis with both the brine benchmark (5,580 USD/t LCE) and the clay project costs reported in this study. We regret that this construction was not made sufficiently explicit in the original submission.

In the revised manuscript, we have clarified the composition of the hard rock benchmark in the Results section, in the captions of Figures 1 and 2, and in the Methods. We have also added the two references suggested by the reviewer (Gao et al., 2023, already cited as Ref. 25; and the Cleaner Engineering and Technology paper now reference 26) to the Introduction and Discussion for additional context on spodumene refining economics.

2. On page 8, line 215, the authors are talking about sulfur as a reagent. It should be clarified that is the sulfur used in sulfuric acid production or somewhere else.

Response: We thank the reviewer for identifying this ambiguity. The sulfur in question is elemental sulfur purchased as feedstock for on-site sulfuric acid production, which in these projects serves a dual function: it produces sulfuric acid for leaching and generates steam and electricity through the exothermic sulfur-burning and SO₃-conversion steps. We have revised the text on first mention of sulfur and added a clarifying note to the Figure 4 caption.

3. The Methods section should come before Results.

We thank the reviewer for this suggestion. We have reviewed *Communications Earth & Environment*'s author guidelines and current article formatting, and the journal permits either Methods-before-Results or Methods-after-Discussion ordering, with recent articles published in the journal following both conventions. We have retained the Methods-after-Discussion structure in the revised manuscript for two reasons. First, it aligns with the formatting of the majority of recent techno-economic and resource-cost analyses published in *Communications Earth & Environment*, which allows readers to engage with the key findings and their implications before encountering the detailed methodological formalism. Second, the methodological contribution of this work, particularly the cost categorization framework, the bilateral and multi-driver sensitivity analysis, and the reagent back-calculation procedure, is most usefully read in the context of the results it supports, rather than in the abstract. To improve navigation for readers who prefer to consult the Methods first, we have added clearer forward references in the Results and Discussion sections (e.g., "as described in detail in the Methods section") at each point where methodological choices affect the interpretation of results. We hope this provides a reasonable compromise between the two structural conventions and improves accessibility regardless of the reader's preferred reading order.

REVIEWER #2:

Thanks for the revised manuscript. The effort to compile project-level data for lithium extraction from clay is appreciated. However, after carefully reviewing the revised version, I still have several fundamental concerns.

Comments:

1. the manuscript remains largely a techno-economic cost analysis, with the main focus on processing costs and optimisation pathways. While this is valuable from an engineering or industry perspective, it does not sufficiently align with the scope of Nature Communications Earth & Environment, which requires a clear contribution to environmental science, Earth systems, or sustainability at a deeper level. The environmental aspects (energy, water, emissions) are presented only as supporting metrics and are not analysed in a comprehensive or mechanistic way.

Response: We appreciate this important comment and agree that the environmental and sustainability framing of the manuscript can be strengthened to better align with the journal's scope. In response, we have made substantive additions to the Introduction and Discussion that more clearly situate this work within the environmental and Earth-systems research agenda, while retaining the cost-focused analytical core of the paper. Specifically, we have

(i) added text in the Introduction that explicitly frames clay-based lithium extraction as a sustainability problem, encompassing critical mineral supply security, land and water disturbance in arid closed-basin hydrogeological systems, and decarbonization of battery supply chains, rather than a purely techno-economic one.

(ii) expanded our engagement with the existing environmental LCA literature on hard rock, brine, and clay lithium, positioning our cost framework as complementary to these environmental analyses and as a foundation for future integrated techno-economic / life-cycle assessments.

We believe these revisions meaningfully strengthen the environmental and sustainability framing of the contribution without duplicating the LCA work that Refs. 46–51 already provide, and that together with the water, energy, and emissions benchmarks in Supplementary Figures S52–S54 they establish the alignment of this work with the scope of *Communications Earth & Environment*.

2. the novelty of the study is limited. The work primarily aggregates publicly available data (feasibility studies and technical reports) and applies standard cost breakdown and sensitivity analysis. There is no clear methodological advancement or new framework that significantly moves beyond existing techno-economic assessments.

Response: We respectfully disagree with the characterization of this work as limited to data aggregation. Our reasoning is as follows:

(i) to our knowledge this is the first systematic, harmonized, process-based cost framework for clay-based lithium extraction spanning three distinct extraction technologies — prior techno-economic studies have addressed hard rock (Gao et al., 2023; Ibarra-Gutiérrez et al., 2021) or geothermal brine (Warren, 2021; Huang et al., 2021) but not clay at this breadth.

(ii) our process-step disaggregation (mineral beneficiation, lithium extraction, purification, Li-salt production) is, to our knowledge, the first to enable cross-technology comparison of where cost burden concentrates within lithium extraction process chains.

(iii) the bilateral isoline sensitivity analysis and the 15-scenario multi-driver break-even framework (Figures 8–9, S15–S50) move beyond single-variable tornado diagrams used in prior techno-economic assessments and provide stakeholders with feasible multi-lever optimization targets rather than single-point estimates.

(iv) the reagent back-calculation from process engineering data (e.g., the Angel Island chlor-alkali analysis in Supplementary Note 1) constitutes a methodological contribution reusable for future studies where public company reporting is incomplete.

3. The study relies heavily on company-reported data, which are inherently uncertain and often optimistic. The manuscript does not adequately address this limitation, and there is no robust treatment of uncertainty (probabilistic analysis), which is critical given the variability in lithium markets and project assumptions

Response: We thank the reviewer for raising this concern, and we agree that data provenance and uncertainty treatment warrant clearer articulation in the manuscript. We would like to respectfully clarify how our study already addresses these issues, and we have added text in the Methods and Discussion to make this more visible to readers. First, our analysis does not rely on any single company report but systematically aggregates primary data across seven independently filed NI 43-101 technical reports spanning three extraction technologies, multiple corporate sponsors, and a range of project-maturity stages (Table 1). The resulting process-technology averages (Table S3) and cost-category comparisons therefore reflect inter-project variation rather than any single company's forecast, which mitigates individual-project optimism bias and provides a realistic central estimate for each extraction route. Second, the manuscript already includes a comprehensive sensitivity and scenario analysis that explicitly varies the major cost drivers, reagent unit costs, power prices, other processing OpEx (including labor), and processing CapEx, to quantify how cost outcomes respond to deviations from reported baseline values. This analysis is presented for each project individually and for each process technology on average (Figure 7 and Supplementary Figures S9–S14), for all bilateral combinations of major cost drivers (Figure 8 and Supplementary Figures S15–S50), and in a systematic 15-scenario multi-driver framework with reductions of 30%, 50%, and 70% (Figure 9). The 30% reduction case effectively corresponds to a $\pm 30\%$ uncertainty envelope around each cost driver, and the 50% and 70% cases extend well beyond the range typically attributed to feasibility-study optimism bias in the mining literature, providing readers with a transparent picture of how cost outcomes respond across a wide range of plausible deviations. Importantly, the qualitative ranking of extraction technologies, sulfate salt roasting < sulfuric acid leaching < hydrochloric acid leaching, is preserved across all sensitivity and scenario variants reported, which supports the robustness of our principal conclusions. Third, we acknowledge the inherent limitations of NI 43-101 company-reported data and the potential for optimism bias in feasibility-stage forecasts, and we have added explicit text on this point in the Discussion (limitations paragraph). We believe the combination of (i) multi-project data aggregation, (ii) comprehensive sensitivity and scenario analysis, and (iii) transparent acknowledgment of data limitations provides an appropriate treatment of uncertainty for the analytical scope of this study, and that a full probabilistic (Monte Carlo) analysis, while a valuable direction for future work, particularly as new primary data become available from operating clay-based projects, is beyond the scope of the present contribution.

4. In addition, the conclusions appear somewhat speculative, particularly regarding the potential cost reductions (up to 50%) required to achieve competitiveness. These improvements are not demonstrated through validated technological pathways or real operational data.

Response: We thank the reviewer for this comment and would like to respectfully clarify that the manuscript as submitted already links the cost-reduction pathways identified in our scenario analysis to concrete technological precedents and to specific emerging technologies documented in the peer-reviewed literature. Specifically, the Discussion section dedicates two paragraphs to this linkage. In the first, we tie reagent cost reductions, the dominant lever in our scenario analysis, to demonstrated closed-loop reagent recycling approaches, citing the chlor-alkali plant at the Angel Island Project (which regenerates HCl and NaOH from waste sodium chloride and is quantified in Supplementary Note 1 and Tables S4–S10), and the sodium sulfate recovery architecture at the Sonora Lithium Project and the Bonnie Claire Lithium Project. These are operational precedents drawn directly from the NI 43-101 technical reports analyzed in this study and demonstrate that the scale of reagent savings assumed in our scenarios is consistent with architectures already in project design. In the second paragraph, we explicitly discuss step-change extraction technologies as pathways toward further cost and environmental reductions, including electrochemical leaching of spodumene, lithium clays, and spent lithium-ion batteries (Refs. 22, 40–42), flash Joule heating (Refs. 43, 44), and high-temperature electrochemistry (Ref. 45), each cited with peer-reviewed evidence of demonstrated reagent and energy-intensity reductions at laboratory or pilot scale. We also discuss process-parameter optimization (retention time, leaching temperature and pressure, reagent concentration, reactor sizing) and digital tools such as real-time process simulation, sensor networks, and AI-assisted predictive maintenance (Ref. 39) as near-term operational levers. Collectively, these discussions already ground the cost-reduction scenarios in operational and technological pathways that are either demonstrated (Angel Island chlor-alkali plant; Sonora / Bonnie Claire sulfate recovery; on-site sulfuric

acid production with integrated steam/power generation at three of the four sulfuric-acid-based projects), documented in peer-reviewed literature (Refs. 22, 39–45), or both. We note that the scenarios in Figure 9 are framed explicitly as break-even cost thresholds required to achieve cost-competitiveness, not as predictions that such reductions will be realized; this conditional framing is already present in the Scenario Analysis section ("to explore pathways for making clay-based lithium extraction cost-competitive ... we first analyzed the sensitivities of major cost drivers") and in the Discussion ("all technologies can achieve cost competitiveness under optimized conditions ... could match global cost averages if reagent, power, and processing costs were reduced by 50–70%"). We hope that the existing treatment sufficiently addresses the reviewer's concern, and we are of course happy to expand on any specific aspect of the technology-pathway linkage that the reviewer believes remains under-supported.

5. Importantly, even from an economic perspective, the central claim of the manuscript (suggested already in the title) that optimisation can make clay-based lithium extraction competitive with conventional sources does not fully reflect the current market reality. Recent developments in the lithium industry show that even well-established conventional operations are facing significant economic challenges. For example, in Australia, which is one of the largest producers of spodumene concentrate, there have been major setbacks including the closure of the Albemarle lithium hydroxide plant, the cancellation of expansion plans at Tianqi's Kwinana refinery, and delays in commissioning of the Covalent lithium project. These examples indicate that even mature and relatively lower-cost lithium supply chains are currently under pressure. In this context, the assumption that more complex and less mature clay-based extraction routes can become competitive through cost optimisation alone appears overly optimistic and insufficiently supported.

Response: We thank the reviewer for this important contextualization and agree that recent developments — the Albemarle Kemerton curtailment, the cancellation of Tianqi's Kwinana refinery expansion, Covalent's commissioning delays, and the broader 2023–2025 lithium price collapse, have material implications for how our findings should be interpreted. We have added a dedicated paragraph to the Discussion addressing this. Specifically, we (i) acknowledge that the price decline has placed pressure across the entire lithium supply chain, including mature hard rock refining operations; (ii) clarify that our benchmark costs (S&P Global, ~5,000–5,580 USD/t LCE) represent production costs, not market prices, and that the cost-competitiveness framing addresses relative production economics rather than project-level profitability at any specific price; (iii) reframe the contribution of the paper accordingly — positioning clay-based extraction as a strategic domestic supply option whose viability depends on targeted process optimization, policy support for supply-chain diversification (as evidenced by the recent 2.26 B USD and 996 M USD DOE loans to Thacker Pass and Rhyolite Ridge), and a lithium price recovery consistent with long-run demand projections; and (iv) softened the framing throughout the Abstract, Results, and Discussion. The title has been retained as it accurately reflects the conditional finding that optimization can make clay competitive, but the text makes explicit that this is contingent on both technological progress and market conditions.

6. The geographical and project scope is limited, with most case studies concentrated in a specific region (primarily Nevada), yet the conclusions are extended to global lithium supply considerations.

Response: We thank the reviewer for this comment and would like to respectfully clarify the rationale for the geographic scope of our study. The concentration of analyzed projects in Nevada (and in Sonora, Mexico) is not a limitation arising from selective inclusion but a direct reflection of the global landscape of publicly reported clay-based lithium projects with primary cost data available at feasibility or pre-feasibility stage. To our knowledge, Nevada is currently the only region in the world where multiple pre-commercial clay-based lithium projects are simultaneously active, in advanced stages of engineering and permitting, and publicly disclosed through NI 43-101 or S-K 1300 technical reports that provide the primary, line-item cost data required for a transparent process-based cost analysis. The Sonora Lithium Project in Mexico is the only publicly reported clay-based project of comparable maturity outside Nevada, and we include it in our study. Other clay-based projects referenced in the literature, for example, the Jadar Project in Serbia, Chinese clay resources, or emerging deposits in Zambia, do not currently have publicly accessible primary cost data of comparable granularity, and including them in our analysis on the basis of secondary or indirect estimates would materially compromise the analytical rigor of the study. The geographic scope of our analysis therefore reflects an objective data constraint rather than a methodological narrowing.

Regarding the benchmarking of our results, we note that the purpose of the paper is precisely to place clay-based lithium extraction, whatever its geographic concentration of current pre-commercial activity, within the context of global lithium production economics. Clay is currently the third largest lithium resource globally, and the question of whether it can become cost-competitive with conventional brine and hard rock sources is inherently a global question, not a regional one. The global benchmarking against S&P Global averages for brine and hard rock production is therefore a deliberate and central element of the study's framing, not an overextension of region-specific findings. The cost drivers we identify, reagent consumption, on-site reagent regeneration, process energy integration, and processing capital intensity, are inherent to the extraction technologies analyzed (hydrochloric acid leaching, sulfuric acid leaching, sulfate salt roasting) and apply wherever these technologies would be deployed. Region-specific factors such as labor costs, energy prices, and regulatory regimes would naturally modulate absolute cost levels in other jurisdictions, but the process-technology cost structures, major cost drivers, and optimization pathways identified in our analysis are methodologically transferable. We believe the current framing of the paper accurately conveys this distinction between the source of primary data and the global relevance of the findings.

REVIEWER #3:

The manuscript presents a solid, well-structured study of high relevance to the field of lithium processing. The analysis is clear and consistent, systematically addressing the economic feasibility of lithium extraction from clays, which is particularly timely given the current growing demand for this resource. The quality of the figures and graphs is especially noteworthy, as they are clear, informative, and facilitate the interpretation of the results as well as the comparison between the evaluated technologies. Furthermore, the level of detail in the study allows for an adequate identification of the main factors influencing process costs. Nevertheless, several aspects could be improved, as detailed below:

1. It is recommended to further elaborate on the justification of the main model assumptions, particularly those related to reagent consumption and process efficiencies. While lines 487–507 describe the use of data from industrial reports, and lines 561–566 mention the estimation of missing data through process parameters, the criteria used for these approximations are not described with sufficient clarity. Considering that these assumptions have a significant impact on the final cost estimates, greater transparency in their definition would strengthen the robustness and reliability of the analysis presented.

Response: We thank the reviewer for this suggestion. The current Methods section already describes our three-tier approach to data handling: (i) direct use of reported values where available; (ii) back-calculation from reported operating parameters where consumption data are missing (reactor/tank sizes, throughput rates, retention times, pumping rates, reaction stoichiometry); and (iii) use of industry averages from analogous projects only where further calculation is not possible. The most detailed worked example — reagent back-calculations for the Angel Island Project's chlor-alkali and lithium processing facility, covering HCl, NaOH, NaCl, and Na₂CO₃ — is provided in Supplementary Note 1 and Supplementary Tables S4–S10, with each calculation step individually documented and cross-referenced to the specific section of the underlying NI 43-101 report. Process efficiencies (lithium recovery rates) used throughout the analysis are taken directly from the corresponding company reports, as listed in Supplementary Information Table S1. To improve visibility of this approach for readers, we have added a short clarifying sentence to the existing Methods paragraph on data handling, pointing readers explicitly to Supplementary Note 1 as the worked example of our back-calculation methodology.

2. It is suggested to deepen the analysis of the leaching process, as it constitutes a key stage in both reagent consumption and operational costs. Although the evaluated technologies are introduced in lines 84–92 and their costs are compared in lines 270–300, the discussion could be expanded to include how operational variables influence these results. In particular, it would be valuable to complement these sections by incorporating the effects of parameters such as pH, temperature, and reagent concentration, as these can affect both extraction efficiency and lixiviant consumption, thereby directly impacting process costs.

Response: We thank the reviewer for this suggestion. The current Discussion already addresses operational leaching parameters directly. The paragraph beginning "*Beyond technology selection, operational optimization provides further leverage for cost control*" identifies retention time, leaching temperature and pressure, reagent concentration, and reactor sizing as the specific operational parameters that directly affect reagent utilization and energy intensity, and it notes that the lower reagent costs at the Rhyolite Ridge Project may reflect optimized process flows. The Methods section further describes the three process-technology temperature regimes quantitatively (50–80 °C for hydrochloric and sulfuric acid leaching; 800–1000 °C for sulfate salt roasting), which is a principal driver of the power-cost asymmetry across technologies reported in Figure 3 and discussed in the Results. Additional operational parameters such as pH control during purification are also addressed in the Methods section on lithium production process steps, which describes the staged carbonate/hydroxide addition governing consumption of calcium carbonate, sodium carbonate, and sodium hydroxide, reagents whose costs are quantified in Figure 4. We believe these existing passages address the reviewer's point, and we are happy to expand on any specific parameter if the reviewer identifies one that remains under-discussed.

3. It is recommended to expand the discussion in the final section (lines 600–650) by incorporating references to emerging leaching approaches that consider both economic and environmental aspects. In this context, the use of alternative complexing agents, such as glycine, has been explored in recent studies, showing promising results in

terms of selectivity and potential reduction in reagent consumption. Although its application has been more widely studied in copper recovery, it has also been proposed for use in lithium-bearing systems, representing an interesting direction for future research. Including these perspectives would enrich the manuscript and provide a more up-to-date view of developments in hydrometallurgical technologies (DOI: 10.3389/fceng.2025.1613424; DOI: 10.3390/met16030248).

Response: We thank the reviewer for this forward-looking suggestion and for the two specific references. The existing final paragraph of the Discussion addresses emerging extraction technologies, including electrochemical leaching (Refs. 22, 44–46), flash Joule heating (Refs. 47, 48), and high-temperature electrochemistry (Ref. 49), framing these collectively as candidate step-change technologies. To incorporate the reviewer's suggestion without adding a separate passage, we have added a brief mention of alternative complexing lixiviants (including glycine-based systems) with the two suggested references to this existing paragraph.

Response to reviewers' comments for:

Optimization of processing costs could improve the cost-competitiveness of lithium extraction from clay relative to conventional sources of brines and hard rock ores

Communications Earth & Environment

We would like to thank the Editor and the Reviewers for taking the time to review our manuscript and for providing constructive comments and suggestions that have greatly helped us further improving the paper. In the following we respond point-by-point to the comments and suggestions provided.

REVIEWER #2:

Comments:

Thanks for the revised manuscript. The effort to compile project-level data for lithium extraction from clay is appreciated. However, after carefully reviewing the revised version, I still have several fundamental concerns.

First, despite the expanded framing, the manuscript remains primarily a techno-economic cost assessment focused on processing costs, benchmarking, and optimisation pathways. The environmental dimensions (water, energy, emissions, and land disturbance) are discussed mainly at a contextual level and are not analysed in a mechanistic or integrated way. As a result, the work still reads more as an engineering and industrial cost-analysis study than as a contribution centred on Earth and environmental systems.

Second, although the authors argue for methodological novelty, the core framework remains based on aggregation and harmonisation of publicly available technical reports combined with conventional cost-breakdown and sensitivity analyses. The additional scenario and isoline analyses improve the presentation of the results but do not fundamentally alter the methodological contribution of the study.

Third, the manuscript still relies heavily on company-reported feasibility data, which are inherently uncertain and often optimistic for pre-commercial projects. While the expanded sensitivity analysis is useful, it does not fully substitute for probabilistic uncertainty treatment or validation against operational performance data. In addition, despite the revised environmental framing, the manuscript still lacks sufficiently comprehensive engagement with the growing body of recent LCA and sustainability literature related to lithium clay resources and unconventional lithium extraction systems. Several recent studies have already investigated broader environmental trade-offs and sustainability implications associated with lithium clay development, yet these perspectives remain only marginally integrated into the present analysis (like doi.org/10.1016/j.jclepro.2024.142955 which compared salt roasting and acid leaching in Thacker Pass and Sonora Projects, there are also other LCA of Li Clay resources worth checking). Consequently, the environmental relevance of the manuscript remains largely contextual rather than analytically embedded within the study framework.

Finally, the conclusions regarding the future competitiveness of clay-based lithium extraction remain somewhat speculative. The manuscript identifies possible optimisation pathways, but these pathways are not demonstrated at a commercial scale and remain dependent on assumptions regarding technological advances, reagent recovery efficiencies, and future process integration. Importantly, even conventional lithium supply chains are currently facing significant economic and operational challenges under present market conditions. In this context, the conclusion that clay-based extraction routes can become broadly competitive through optimisation alone still appears insufficiently supported.

Response: We thank the editor and Reviewer #2 for their continued careful reading. Following the editor's guidance, we have taken the first of the two offered options, moderating the strength of our competitiveness claims, rather than attempting to substitute commercial-scale performance data, which does not yet exist for any of the pre-commercial projects analyzed. We have also strengthened our engagement with the recent life-cycle literature, including the specific study the reviewer identified. We address each point below.

On the competitiveness claims being speculative. We agree that our optimization pathways are not demonstrated at commercial scale, and we have revised the manuscript so that this is stated explicitly at every point where a competitiveness claim appears, rather than only in the caveat paragraphs. Specifically, we:

- (i) Softened the title from "can make...competitive" to "could improve the cost-competitiveness of";
- (ii) Revised the strongest Discussion statement so that the three technologies are described as able to "in principle, approach cost-competitiveness under substantial and concurrent cost reductions that remain to be demonstrated at commercial scale"
- (iii) Reframed the 3,200 USD/t LCE scenario as an idealized upper-bound target rather than a projection;
- (iv) Added a statement at the opening of the scenario analysis that these pathways are conceptual and are offered as targets to guide technology development, not as evidence of present competitiveness. We believe these changes bring the headline claims into line with the market-context and uncertainty caveats already present, directly satisfying the editor's condition.

On the environmental/Earth-systems dimension not being analyzed mechanistically. We take the reviewer's point but note that the manuscript is framed, and was accepted in principle, as a techno-economic cost analysis "designed to be read alongside" life-cycle work, not as an integrated environmental assessment. Rather than expand the study's scope, we have sharpened the connection to the environmental literature (below) and made explicit where the cost drivers we identify coincide with the environmental drivers reported in recent LCAs.

On engagement with recent LCA/sustainability literature, including [10.1016/j.jclepro.2024.142955]. We have added and engaged Khakmardan et al. (2024, *J. Cleaner Production* 467, 142955), which performs an LCA of sedimentary lithium-clay projects including Sonora and Thacker Pass, the same projects analyzed here. We note in the Discussion that this study finds environmental impacts to be governed primarily by electricity sourcing and by on-site sulfuric-acid/power integration, i.e. the same levers that dominate our cost results. This lets us show concretely that the cost-reduction pathways we identify (reagent recovery, on-site acid/power integration, cleaner electricity) are also the principal environmental-improvement pathways, reinforcing the value of coupled techno-economic and life-cycle assessment.

On reliance on feasibility-stage data and the absence of probabilistic uncertainty treatment. We retain our multi-report aggregation and 20–70% sensitivity/scenario framework as the study's uncertainty treatment, and we have made explicit (Methods and Discussion) that formal probabilistic uncertainty quantification and validation against operational data are deferred to future work as such data become available from projects now under construction. We have added language framing our figures as production-cost estimates, not price forecasts or profitability claims.

On methodological novelty. We agree the core contribution is the systematic harmonization and process-step decomposition of otherwise non-comparable feasibility reports across three extraction routes, plus the scenario framework. We have tempered any language implying a fundamentally new method and instead position the contribution as the first like-for-like, process-resolved cost benchmark for clay-based lithium with a transparent optimization-pathway framework.

We hope these revisions, which preserve the study's cost-analysis scope while moderating the competitiveness claims as the editor suggested, are now suitable for publication.

Reviewer Comments on the Manuscript

The manuscript presents a solid, well-structured study of high relevance to the field of lithium processing. The analysis is clear and consistent, systematically addressing the economic feasibility of lithium extraction from clays, which is particularly timely given the current growing demand for this resource. The quality of the figures and graphs is especially noteworthy, as they are clear, informative, and facilitate the interpretation of the results as well as the comparison between the evaluated technologies. Furthermore, the level of detail in the study allows for an adequate identification of the main factors influencing process costs.

Nevertheless, several aspects could be improved, as detailed below:

1. It is recommended to further elaborate on the justification of the main model assumptions, particularly those related to reagent consumption and process efficiencies. While lines 487–507 describe the use of data from industrial reports, and lines 561–566 mention the estimation of missing data through process parameters, the criteria used for these approximations are not described with sufficient clarity. Considering that these assumptions have a significant impact on the final cost estimates, greater transparency in their definition would strengthen the robustness and reliability of the analysis presented.
2. It is suggested to deepen the analysis of the leaching process, as it constitutes a key stage in both reagent consumption and operational costs. Although the evaluated technologies are introduced in lines 84–92 and their costs are compared in lines 270–300, the discussion could be expanded to include how operational variables influence these results. In particular, it would be valuable to complement these sections by incorporating the effects of parameters such as pH, temperature, and reagent concentration, as these can affect both extraction efficiency and lixiviant consumption, thereby directly impacting process costs.
3. It is recommended to expand the discussion in the final section (lines 600–650) by incorporating references to emerging leaching approaches that consider both economic and environmental aspects. In this context, the use of alternative complexing agents, such as glycine, has been explored in recent studies, showing promising results in terms of selectivity and potential reduction in reagent consumption. Although its application has been more widely studied in copper recovery, it has also been proposed for use in lithium-bearing systems, representing an interesting direction for future research. Including these perspectives would enrich the manuscript and provide a more up-to-date view of developments in hydrometallurgical technologies (DOI: 10.3389/fceng.2025.1613424; DOI: 10.3390/met16030248).