

How can prospective life cycle assessment support the eco-design of an innovative battery-grade lithium carbonate production process?

Original

How can prospective life cycle assessment support the eco-design of an innovative battery-grade lithium carbonate production process? / Sakatadi, N.G., Beylot, A., Lai, F., Hippmann, S., Pavón, S., Blengini, G.A.. - In: RESOURCES, CONSERVATION & RECYCLING ADVANCES. - ISSN 2667-3789. - 237:(2027). [10.1016/j.resconrec.2026.109179]

Availability:

This version is available at: 11583/3016464 since: 2026-10-09T15:37:31Z

Publisher:

Elsevier

Published

DOI:10.1016/j.resconrec.2026.109179

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)



Full length article

How can prospective life cycle assessment support the eco-design of an innovative battery-grade lithium carbonate production process?

Gyslain Ngadi Sakatadi ^{a,*}, Antoine Beylot ^b, Frédéric Lai ^b, Sebastian Hippmann ^c, Sandra Pavón ^c, Gian Andrea Blengini ^{a,d}

^a Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, Torino, 10129, Italy

^b BRGM - French Geological Survey, Orléans, F-45060, France

^c Fraunhofer Institute for Ceramic Technologies and Systems IKTS, Fraunhofer Technology Center for High-Performance Materials THM, Freiberg, 09599, Germany

^d University of Turin, Earth Sciences Department (DST), Via Valperga Caluso, 35, Torino, 10125, Italy

ARTICLE INFO

Keywords:

Battery-grade lithium carbonate
Life cycle assessment
Environmental impacts
Eco-design strategies
Critical raw materials
Supercritical CO₂ leaching

ABSTRACT

The transition to low-carbon energy systems drives increasing lithium demand, making alternative recovery technologies essential for long-term supply resilience. This study shows how eco-design principles guide the identification of the most environmentally-friendly configuration, supporting future mitigation-oriented design choices. Three innovative lithium recovery routes, distinguished by their concentration-stage configurations, are assessed: Route A uses reverse osmosis with impurity removal, Route B excludes membrane technology, and Route C applies nanofiltration without prior impurity removal. Life cycle assessments are conducted considering decarbonised background systems and process circularity, including resource and energy efficiency in the foreground system. The most effective eco-design strategy delivers potential reductions in climate-change impacts of ~21% through foreground improvements, ~60% through background improvements, and up to ~68% when combined from the current to the optimised future scenario. Residual impacts further highlight the need for additional eco-design strategies. Sensitivity and uncertainty analyses evaluate key factors, including ore-grade variability and data quality.

1. Introduction

The importance of lithium to a low-carbon economy, particularly in decarbonising the automotive sector, drives its increasing demand (Hund et al., 2020). Global lithium demand could increase over fortyfold by 2040 under climate-aligned scenarios (IEA, 2021). At the same time, the EU continues to rely heavily on Chile, which supplies about 79% of its lithium imports (European Commission, 2023). Regional sourcing is therefore fundamental for future supply security. Achieving this requires both the deployment of emerging extractive technologies and robust environmental assessment to align with existing policies and initiatives, including the Critical Raw Materials Act targets (European Commission, 2023), in particular those related to increasing domestic extraction and processing capacities within the EU.

The Life Cycle Assessment (LCA) framework (ISO, 2006b, 2006a) is commonly adopted to assess the environmental impacts of raw materials production, whether at the level of processes under development (Beylot et al., 2021b), operating sites (Lai et al., 2021) or global supply-chains

(Lai et al., 2026; Nuss and Eckelman, 2014). Lithium compounds, particularly lithium carbonate (Li₂CO₃) and lithium hydroxide monohydrate (LiOH·H₂O), are mainly produced from hard-rock ores and salt brines. LCA studies by Chordia et al. (2022), Kelly et al. (2021), Mas-Fons et al. (2024) and Stamp et al. (2012) on conventional lithium production pathways indicate that brine-based lithium production generally exhibits a high water footprint and lower climate change impacts than ore-based routes. The acid-leaching method is the most common approach for producing battery-grade lithium carbonate (Li₂CO₃) from ores (Meng et al., 2021; Światowska and Barboux, 2015). Recent advances increasingly focus on reducing reagent use (Dahlkamp et al., 2024; Mende et al., 2023; Pavón et al., 2021b, 2022; Petrakis et al., 2025). The pressure-leaching method is also gaining attention as a more environmentally friendly alternative to conventional acid-leaching methods (Lappalainen et al., 2025, 2024).

Future-oriented LCAs, commonly referred to as prospective LCAs in the literature (Arvidsson et al., 2024) and in this study, seek to assess the potential environmental impacts of emerging technologies under future

* Corresponding author.

E-mail address: gyslain.sakatadi@polito.it (G.N. Sakatadi).

<https://doi.org/10.1016/j.resconrec.2026.109179>

Received 26 January 2026; Received in revised form 23 July 2026; Accepted 20 September 2026

Available online 27 September 2026

0921-3449/© 2026 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

conditions. These assessments are characterised by high uncertainty due to limited primary data availability and variable data quality, including data upscaling (Tsoy et al., 2020) and scenario development (Langkau et al., 2023), particularly in early development phases (Arvidsson et al., 2018; Buyle et al., 2019; Moni et al., 2020; Thonemann et al., 2020). Factors related to technology maturity, especially those associated with Technology Readiness Levels (TRL) and Manufacturing Readiness Levels (MRL), strongly influence uncertainty in prospective LCA. Nevertheless, early-stage LCA remains essential to identify environmental hotspots and inform process design choices, while design flexibility is still high.

Despite these advances, most existing prospective LCA studies of novel lithium production systems (e.g. Iyer et al., 2026; Nikfar et al., 2025; Nishikawa et al., 2026) rely on comparative or scenario-based assessments using largely static process representations. While these approaches provide valuable insights into environmental hotspots and technology benchmarking, they generally remain limited in capturing the dynamic interaction between key process factors, such as recovery efficiency ranges, feed characteristics (e.g., ore grade variability), and process circularity (e.g., reagent and water recirculation potentials), as well as potential background system evolution, reflecting robust prospective narratives, such as those induced by Integrated Assessment Model (IAM)-based background transformations (Mendoza Beltran et al., 2020). Thus, the individual and combined effects of

process-level optimisation and future system changes remain partially explored, particularly for innovative lithium recovery systems from unconventional ore feedstocks.

In this context, an early-stage lithium (Li) recovery technology is assessed at an intermediate scale (TRL 5) using a prospective LCA approach. The approach integrates foreground production route configurations and key influencing factors with evolving background systems to assess the independent and combined effects of process optimisation and future system changes. The initial process, patented for the selective recovery of lithium using supercritical CO₂ leaching, was originally developed for zinnwaldite (DE102015221759A1), and applies high-pressure CO₂ carbonation to yield Li₂CO₃. It has since been adapted and optimised to operate with spodumene as well, which constitutes the focus of the present study. It integrates a pressure-leaching approach, as demonstrated by Mende et al. (2023) and Pavón et al. (2022, 2021b, 2021a), together with alternative concentration pathways for Li₂CO₃ production, applied to both regional (EU-based) and external unconventional feedstocks, as a simplified alternative to conventional acid-based pathways, while reducing process complexity (Pavón et al., 2026).

The objective of this study is to evaluate the potential environmental impacts associated with the process across different technological routes and scenarios within a prospective LCA framework to support eco-design. Extending beyond recent studies applying eco-design mainly

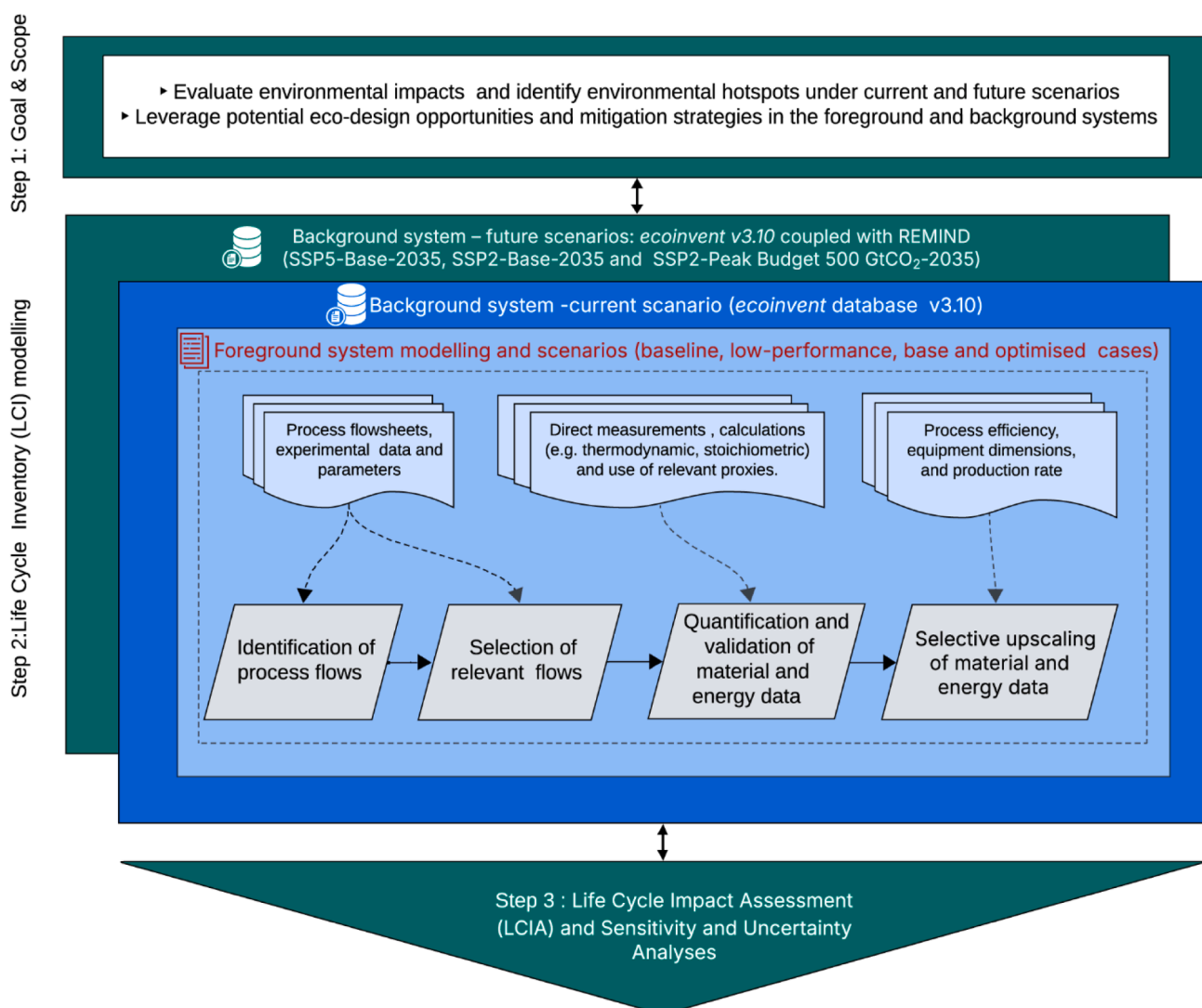


Fig. 1. Overview of the sequential approach adopted for the prospective LCA.

through LCA-based optimisation or simulation (e.g., Ashraf et al., 2026; Liu et al., 2026; Sun et al., 2025), this framework integrates parameterised foreground variations with evolving background scenarios. The approach further extends the principles of emerging EU eco-design frameworks under the Ecodesign for Sustainable Products Regulation (ESPR) and is aligned with life cycle-based hotspot identification and trade-off assessment (European Commission, 2025). This enables quantification of potential impact ranges, distinguishing contributions from process-level improvements and broader system changes, and identifying hard-to-abate impacts across different scenarios and time horizons, thereby supporting more robust decision-making and early identification of mitigation strategies under policy-driven scenarios.

2. Methods and data

The LCA approach adopted in this study follows the ISO 14040–14044 framework (ISO, 2006a, 2006b). Fig. 1 presents an overview of the LCA modelling approach adopted for this study.

2.1. Step 1: Goal and scope definition

This study aims to compare three distinct process routes to identify the environmentally best-performing configuration, while quantifying the potential range of environmental impacts and identifying key hot-spots associated with the Li_2CO_3 production process. A prospective LCA is therefore conducted to support process development and improvement by identifying eco-design opportunities and informing early-stage decision-making. The functional unit (FU) is defined as the production of 1 kg of battery-grade Li_2CO_3 (purity >99%), based on the product quality achieved during experimental testing. The system is mono-functional, with Li_2CO_3 as the sole product; therefore, no multi-functionality arises, in line with ISO 14040/44. It covers process stages from spodumene ore mining to the production of the final product. These models build on current development stage (TRL 5) insights to approximate industrial conditions (TRL 8-9) as closely as possible under different scenario cases across three distinct process routes.

2.1.1. Process description

The lithium recovery process comprises five stages: comminution, thermal treatment, leaching, concentration, and purification. Ore grades from experimental tests were considered, with lithium contents ranging from 0.4 wt.% Li for spodumene ore from Spain to 1.44–3.12 wt.% Li for spodumene ore from Nigeria. The highest-grade material was used as the reference feedstock for the LCA models to represent favourable operating conditions. This is consistent with the current process design, which is better suited to medium-to-high-grade feedstocks due to the absence of pre-concentration steps (e.g., flotation). Additional ore grades were also considered to capture variability and improve representativeness across different feed qualities.

The unit processes and their associated material and energy flows are structured around three distinct alternatives in the concentration stage: Routes A and C use membrane technology for pre-concentration, whereas Route B employs non-membrane technology for the pre-concentration step prior to crystallisation. Fig. 2 presents the process flowchart for battery-grade Li_2CO_3 production across the three production routes considered in this study. Detailed process flowsheets for each route are provided in the Supplementary Information (SI-1), including the mineralogical composition, while the chemical composition of the spodumene ore feedstocks based on XRD and XRF analyses, as well as detailed descriptions for each process stage, are provided in Tables S1 and S2, respectively.

2.2. Step 2: Life cycle inventory modelling

2.2.1. Foreground system modelling

In the foreground system, three scenario cases were defined based on key elements that are sensitive to higher TRL and MRL levels, building on experimental observations and evidence, particularly the Li recovery efficiency and the potential for internal recirculation and reuse of process streams. It involves specifically (i) Li recovery in the leaching unit, (ii) water recovered from the crystallisation and washing units, and (iii) sodium carbonate (Na_2CO_3) recovered at the final stage and reused in the calcination unit. These scenario aspects, in turn, reflect experimentally observed performance variations at the current development stage (TRL

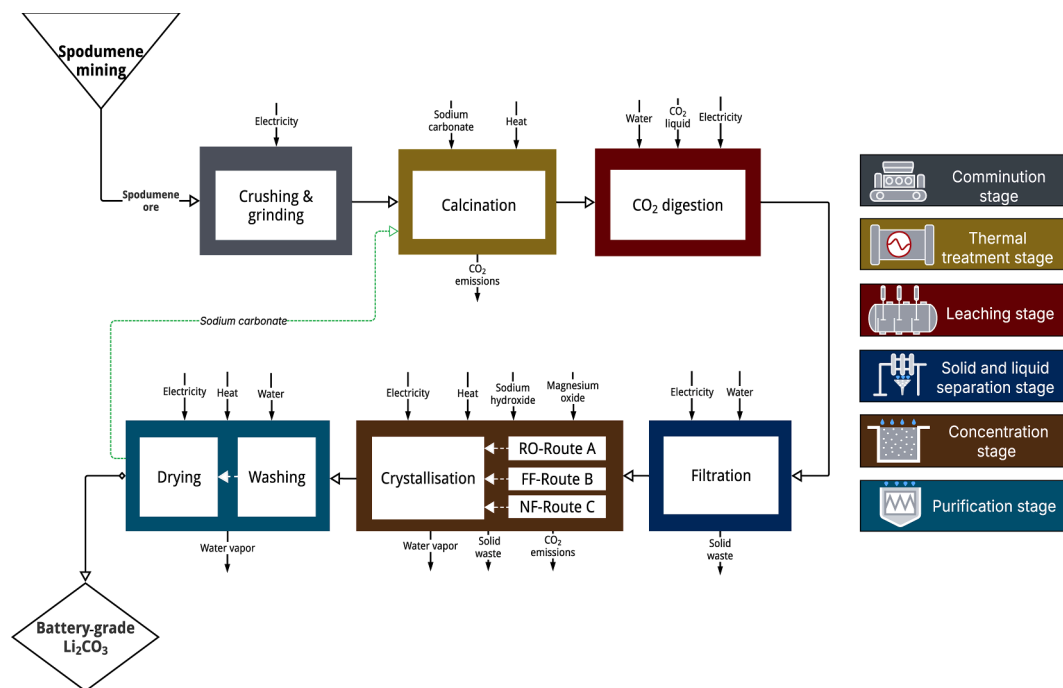


Fig. 2. Process flowchart for the battery-grade lithium carbonate production process, illustrating three distinct alternatives for the pre-concentration prior to crystallisation in the concentration stage: Route A – reverse osmosis (RO), Route B – fine filtration (FF), and Route C – nanofiltration (NF).

5). In addition, the selected ranges are defined by operating limits, building on the current state of process development, including expert insights. They therefore represent bounded operating conditions during process optimisation and scale-up, rather than fixed predictions of future industrial-scale performance. The foreground scenario cases were constructed as follows:

- **Low-performance case (LP):** reflects the lowest lithium recovery achieved (57%) in the leaching unit during experimental work, with no recirculation of Na_2CO_3 or process water considered.
- **Baseline (BL):** represents a technically achievable lithium recovery rate (82%) in the leaching unit, with Na_2CO_3 reuse of 22% and no recirculation of water vapour, reflecting current process performance. This configuration remains identical across scenarios and is combined with different background systems (see Section 2.2.2). In future scenarios, this same foreground configuration is referred to as the base case (BC) to distinguish it from the current background context.
- **Optimised case (OPT):** considers the maximum lithium recovery achieved (94%) in the leaching unit during experimental work, with Na_2CO_3 recovery of 67%, reflecting the highest potential performance and full internal water recirculation from the crystallisation and washing units, consistent with industrial-scale vapour recovery systems.

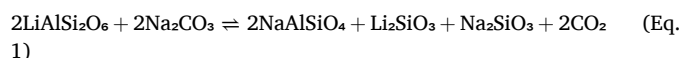
An overview of overall lithium recovery efficiency across the different scenario cases is provided in Table S4 (SI-1), where lithium recovery rates of 90 %, 50 %, and 35 % are achieved in the concentration stage for Routes A, B, and C, respectively. Taken together, for the low-performance, base case, and optimised cases, respectively: Route A achieved lithium recoveries of 51.3%, 73.8%, and 84.6%; Route B, 28.5%, 41%, and 47%; and Route C, 20%, 28.7%, and 32.9%. Under the optimised case, Route A achieves an overall lithium recovery comparable to the conventional roasting and acid-leaching route, which typically achieves over 85% (Swain, 2017).

The Life Cycle Inventory (LCI) development followed a stepwise approach (Fig. 1). Process flows were identified from process flowsheets and experimental insights. Inventory quantification followed a data-quality-based hierarchy, prioritising reliable and available sources (Parvatkar and Eckelman, 2019). Selective upscaling was applied jointly with data quantification to represent projected industrial-scale conditions using an empirical approach. Within this framework, detailed aspects related to equipment design (e.g., leaching reactor configuration), system integration (e.g., energy flow integration), and equipment-level efficiencies are represented through available experimental data and mini-pilot insights, including scaling relationships and literature-based proxies, rather than being explicitly resolved at the full industrial engineering design level. The data quantification hierarchy was as follows:

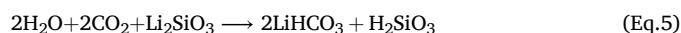
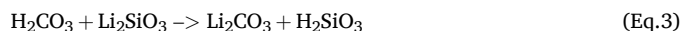
- **Direct measurements:** prioritised wherever available, derived from experimental mass balance data, with empirical scaling applied only to flows identified as scale-dependent.
- **Process-based estimates:** applied when direct measurement was not feasible. These were quantified estimates derived from process parameters and empirical scale-up factors, based on thermodynamic calculations. Stoichiometric calculations based on balanced equations were also used to derive these estimates. Excess reactants were incorporated to account for potential system losses and process inefficiencies, as informed by experimental observations.
- **Proxies:** used only when neither direct measurements nor estimates could be established. In such cases, representative values were taken directly from the literature based on comparable large-scale or mature industrial processes.

2.2.1.1. Mining and comminution stages. The spodumene ore feed requirement, consistent with the FU, was determined based on ore grade and overall process Li recovery efficiency. Inventory data related to spodumene mining were retrieved from Khakmardan et al. (2025), used as a representative proxy for spodumene extraction under comparable system conditions. Potential regional variability (e.g., geographical conditions and operational practices) is acknowledged and addressed through uncertainty analysis. Energy use for crushing and grinding was estimated using Kick's Law and the Bond Work Index (Gupta and Yan, 2016; Wills and Finch, 2016). This is based on established comminution relationships and experimental parameters, and is considered representative of industrial-scale operation.

2.2.1.2. Thermal treatment stage. For the transformation of α - to β -spodumene, the Na_2CO_3 requirement to improve Li mobilisation during this stage was determined from experimental mass balance data. Part of this Na_2CO_3 input is recovered at the final stage together with the Li_2CO_3 product. CO_2 emissions, corresponding to about 8 % of the initial feed, were estimated stoichiometrically from Eq. 1. The thermal energy demand was calculated from process parameters using the first law of thermodynamics and empirically scaled proxies (Piccinno et al., 2016), where temperature and material properties are based on experimental data, while heat losses and system efficiencies are approximated using literature-derived empirical industrial parameters. The reaction can be represented as follows:



2.2.1.3. Leaching stage. In the leaching stage, material requirements were defined from mass balance based on experimental data. The CO_2 input corresponds to the stoichiometric amount required for leaching, including an additional 10 % margin to account for system losses and operational requirements under supercritical conditions, where continuous CO_2 supply is needed to maintain pressure and reaction conditions (Hansel et al., 2026). These conditions are characterised by high diffusivity and enhanced mass transfer properties, based on experimental observations, expert knowledge, and supported by literature (Ndlovu et al., 2025). Water use was also derived from mass balance, corresponding to an empirical ratio observed during experimental tests. Electricity demand was measured directly from the mini-pilot autoclave reactor and scaled up using empirical power-law relationships to reflect larger reactor performance (Caduff et al., 2011), capturing non-linear scaling behaviour and improved energy efficiency at industrial reactor volumes. The leaching reactions can be expressed as follows:



2.2.1.4. Solid and liquid separation stage. During the filtration stage, where the solid residue is separated from the lithium bicarbonate (LiHCO_3) solution, additional water is used only in Route B. Its quantity was determined through mass balance calculations based on experimental measurements. Electricity demand was estimated using an industrial proxy (SUEZ, 2025), considered to be representative of large-scale filter press operations under continuous solid-liquid separation conditions. These systems operate under batch or semi-continuous conditions and are considered representative in terms of separation mechanism and energy demand.

2.2.1.5. Concentration stage. The concentration stage required different material and energy inputs across the three routes. In Route A, impurities were removed prior to reverse osmosis, primarily through pH adjustment and the addition of silica control and removal reagents, namely sodium hydroxide (NaOH) and magnesium oxide (MgO). Routes B and C required no chemicals. Energy demands were estimated using thermodynamic calculations and scaled proxies (Al-Karaghoul and Kazmerski, 2013; Piccinno et al., 2016; Rivero-Falcón et al., 2025), where membrane separation and evaporation processes are approximated using data from comparable large-scale water treatment and mineral processing systems. Due to membrane integration, ~25% of the solution entered crystallisation in Routes A and C, whereas the full stream was treated in Route B, increasing energy demand for crystallisation. Emissions were derived from mass balance calculations based on experimental work and Eq. 6. The overall reaction can be expressed as follows:



2.2.1.6. Purification stage. To obtain battery-grade Li_2CO_3 (purity > 99.5%), the raw Li_2CO_3 product was purified using water, which varies across process routes depending on impurity levels, particularly sodium (Na). Water input and resulting water vapours were determined from experimental mass balance data. Energy demand for Routes A and C was estimated using thermodynamic calculations. Route B was modelled using multiple-effect drying (MED), based on an industrial proxy derived from Al-Karaghoul and Kazmerski (2013), based on integrated multi-effect evaporation systems. While specific data for multi-effect drying are limited, the proxy assumes a similar heat-cascade mechanism widely used to improve energy efficiency, providing a reasonable approximation for this process.

Further details on data sources, including experimental measurements, calculations (e.g., data, formulas, equations), scaling considerations, and proxies used for each process flow are provided in Appendix B (SI-1, Table S5). Accordingly, core process parameters (e.g., recovery and mass balances) are supported by experimental data at TRL 5, while energy demand and equipment-related aspects are based on scale-up assumptions and literature proxies.

2.2.2. Background system modelling

The background system was modelled using the *ecoinvent* v3.10 database (Wernet et al., 2016), using the cut-off by classification system model, where background multifunctionality is resolved through subdivision where possible or, otherwise, allocation among co-products according to the database methodology. All production was assumed to occur on the same site, and Spain was selected as the geographical context. Spain was selected to represent a prospective European setting for lithium, while the single-site assumption reflects an integrated industrial set-up consistent with the prospective scope of the study. The focus is placed on process-level impacts and isolating process performance from site-specific logistics (e.g., transport between process steps), which are therefore neglected. In addition, at the mid-development stage, all processes ran on electricity. For industrial upscaling, energy sources were adapted to reflect typical industrial practices: calcination was modelled using heat from natural gas, while crystallisation and drying in Route B used heat from steam. All other operations remained electricity-based. Electricity, water, and energy supply are modelled using datasets representative of the Spanish context, prioritised when available. Waste is assumed to be disposed of on-site (e.g., through backfilling).

For the development of future scenarios, the year 2035 was selected as the reference horizon, representing the estimated timeframe by which the process could realistically reach industrial-scale implementation given its current development stage. Accordingly, the *ecoinvent* database

was transformed using Premise (Sacchi et al., 2022), run within Brightway2 (Mutel, 2017), to generate prospective background databases reflecting projected future changes (e.g., electricity mix). The premise tool transforms the *ecoinvent* database by updating datasets for the energy and fuel sectors, transport, and heavy industry (e.g., steel production), integrating carbon capture and storage systems, adjusting process efficiencies, and modifying hotspot pollutant emissions (Sacchi et al., 2022). This approach combines Integrated Assessment Models (IAMs) with Shared Socioeconomic Pathway (SSP) and Representative Concentration Pathway (RCP) narratives to support consistency with global climate targets and long-term energy-transition pathways. The background system considered includes one current scenario and three future-oriented background scenarios, defined as follows:

- **Current production:** *ecoinvent* database v3.10, representing the status quo production.
- **Fossil-intensive pathway:** REMIND-SSP5-Base, representing a potential fossil-fuel-driven pathway with rapid economic growth, heavy dependence on conventional energy without climate mitigation policies.
- **Current policy pathway:** REMIND-SSP2-Base, reflecting continuation of existing trends, “a middle-of-the-road” pathway that follows historical trends without additional climate action.
- **High ambition pathway:** REMIND-SSP2-Peak Budget 500 GtCO₂, reflecting sustainability focus in alignment with the Paris Agreement target of limiting global warming to 1.5°C, with a peak carbon budget of about 500 Gt CO₂.

Current and future LCA scenarios were developed by combining independently defined foreground (FG) and background (BG) configurations within a structured scenario matrix. Aligned combinations are used as representative cases: low-performance with fossil-intensive pathways, base case with current policy trajectories, and optimised scenarios with high-ambition pathways. These combinations reflect plausible co-evolution between technological development and broader system transitions, while alternative combinations remain possible.

On this basis, the current scenario combines the baseline foreground inventory with the *ecoinvent* v3.10 database, representing the post-upscaling status quo under static system performance of the production process, hereafter referred to as the baseline LCA scenario case. On the other hand, future scenarios combine low-performance, base-case, and optimised foreground cases, with prospective background databases representing a fossil-intensive pathway, a current policy trajectory, and a high-ambition pathway, respectively. Overall, this results in the baseline, low-performance, base-case, and optimised LCA scenario cases. This structured scenario design, therefore, enables both the interpretation of aligned scenarios, including the assessment of the independent and combined effects of foreground and background changes on environmental performance. An overview of the LCA scenarios is provided in Table S6 (SI-1).

2.3. Step 3: Life cycle impact assessment and sensitivity analysis

2.3.1. Environmental impact assessments

The Life Cycle Impact Assessment (LCIA) was conducted using the Environmental Footprint (EF) method, version 3.1. Impact categories were selected based on their relevance to the process under study and in line with sectoral recommendations (Santero and Hendry, 2016). The selection prioritises categories that are relevant to the mineral and metal sector and sensitive to key process factors and modelling considerations (e.g., water use, waste management, and lithium recovery efficiency), as these are most informative for eco-design decision-making, particularly in the context of this process transitioning towards industrial scale.

Accordingly, the water use category was also included, given the high-water demand observed in some scenarios, particularly those with low-grade spodumene feedstock. Freshwater ecotoxicity is also included

to capture potential impacts associated with impurity releases and waste management strategies under different process configurations. To complement these impact categories, the dissipation-based framework and method were applied (Beylot et al., 2021a). This approach accounts for potentially dissipated lithium flows that remain inaccessible due to emissions to the environment (e.g., tailings disposal) and to current technological limitations within the foreground system (Beylot et al., 2020). These flows were quantified through mass balance calculations across process stages and are reported at the process level. This indicator should be interpreted as a measure of resource accessibility and recovery efficiency rather than an immediate environmental impact. This approach was preferred over abiotic resource depletion, as it more directly captures lithium losses and resource accessibility concerns, particularly for mineral recovery processes at low- to mid-TRL.

While all EF 3.1 categories may be relevant in other contexts, ozone depletion, human toxicity, ionising radiation, and land use were not prioritised, as they are less relevant to the system under study and less consistent with broader sectoral guidelines and recommendations. For instance, in mineral and metal production, human toxicity is more relevant for sulfidic systems (e.g., copper production) with heavy metal emissions, which are often not present in the spodumene-based process, including tailings management (Beylot et al., 2022). The full rationale for inclusion and exclusion of impact categories is summarised in SI-1 Table S11. Based on these considerations, the selected impact categories were: Climate change (CC), Acidification (AC), Terrestrial eutrophication (EUTT), Freshwater eutrophication (EUFT), Marine eutrophication (EUTM), Freshwater ecotoxicity (ET), Water use (WU), Particulate matter formation (PM), Photochemical ozone formation, human health (POF), and the JRC-LCI dissipation-based method. Environmental impacts were calculated using the Activity Browser software (Steubing et al., 2020).

2.3.2. Sensitivity and uncertainty analyses

Potential changes in the foreground system were examined through a sensitivity analysis. The sensitivity analysis variables (SA-VARS) were defined based on key process inputs likely to change and expected to have a strong influence on the results. Table S12 (SI-1) presents the SA-VARS, including their variation ranges and the rationale for their selection and definition. The sensitivity ranges reflect anticipated potential future variation informed by process-development observations, supported, where applicable, by literature evidence and expert judgement. The ranges were defined based on the expected limits of process operations and their equipment. For instance, calcination temperatures range from 600 to 900°C, with 750°C as the optimal value. These values are based on experimental insights, where adequate mineral transformation occurs across this range, while 750°C corresponds to the optimal spodumene phase-transformation temperature. In addition, the influence of ore-grade variation was assessed for each production route and scenario. Ore-grade differences reflect natural deposit inhomogeneity. This aspect also aligns with projected market trends, indicating a gradual decline in average ore grades for future lithium production (Harpprecht et al., 2024).

Furthermore, uncertainty analysis was incorporated to account for further variability and data quality differences in the foreground system. Parameter-specific distributions were assigned, assuming triangular distributions for experimental and calculated data, informed by the SA range rationale definition, and lognormal distributions with pedigree scoring for proxy-based inputs (Lai et al., 2026; Muller et al., 2016). Uncertainty associated with the adopted scale-up protocol is implicitly captured within the defined parameter ranges. In addition, production pathway variability is addressed through the foreground configurations and prospective background pathways defined in the previous section, thereby capturing alternative development trajectories. The uncertainty rationale, parameter ranges, and distribution assumptions are reported in SI-1, Table S13.

3. Results and discussion

3.1. Scenario-based life cycle inventories

The LCIs developed from the established foreground scenarios reveal clear differences in energy and material requirements (Table 1). Routes B and C consume up to three times more energy than Route A, mainly due to lower lithium-recovery efficiency in the concentration stages. Energy required to produce 1 kg of Li_2CO_3 ranges, across the LP, BL, and OPT cases, from 21–40 kWh of electricity and 11–21 MJ of heat for Route A, 37–71 kWh and 59–99 MJ for Route B, and 52–100 kWh and 27–53 MJ for Route C, respectively. Overall, Route A shows greater resource- and energy-efficiency viability for future development.

3.2. Sensitivity-based variations in the foreground inventories

The SA variables introduce moderate shifts in the LCIs. Energy-related SA variables drive the largest changes, followed by chemicals and water use in the concentration and purification stages. The demand for minerals, chemicals, and water resources, including energy inputs, rises as ore grade declines across all scenarios. The change is modest between 3.12% and 2.86% Li, becomes more noticeable at 2.0% and 1.44%, and becomes sharp at 0.4%, where process electricity, heat, water, minerals, and chemicals increase by approximately $5\text{--}8\times$ across all routes and cases relative to the highest grade. This pattern is consistent across all routes and cases. Overall, ore grade remains the dominant driver of energy and materials intensity, covering minerals, chemicals, and water resources, while process performance determines whether these increases are amplified or moderated. LCIs for producing 1 kg of Li_2CO_3 across all SA cases and ore-grade variations are provided in Tables S14–S19 (SI-1). Feed characteristics beyond ore grade, such as impurity levels, can also influence process performance. How these variations affect process requirements warrants further investigation.

3.3. Environmental impact results

This section presents the range of environmental impacts, with emphasis on CC-related hotspots, while the selected impact categories are compared to identify the best-performing process configuration. The remaining EF 3.1 impact categories are reported in SI-2 and do not alter the identification of the best-performing process configuration, supporting the robustness of the selected impact categories for the comparative assessment.

3.3.1. Current scenario cases

Environmental impact ranges, as illustrated in Fig. 3, show that under current scenarios, Route A has the lowest climate change impact, followed by Routes B and C, with estimated impacts of 19.9, 23.7, and 26.2 kg $\text{CO}_2\text{-eq/kg Li}_2\text{CO}_3$, respectively. Input-level contribution analysis indicates that in Route A, NaOH used in the concentration stage is the dominant contributor to CC impacts, representing approximately 40.6 %. In Route B, electricity consumption during leaching is the primary contributor, accounting for approximately 40.2 %. Route C shows a similar profile, with electricity during leaching as the main contributor, contributing approximately 51.2%. The leaching and concentration stages dominate impacts across all routes. Taken together, energy inputs account for 32.8–70 % of CC impacts, while chemical inputs contribute 14.3–57.2%, with minor contributions from other process inputs. Although energy demand is higher in Routes B and C, overall CC impacts remain relatively close because NaOH use dominates Route A, while electricity use dominates Routes B and C, and these hotspots partly offset the differences arising from their distinct process configurations.

The findings in terms of impact ranges are consistent with the literature; for example, Kelly et al. (2021) report a CC impact of 20.4 kg $\text{CO}_2\text{-eq kg}^{-1} \text{Li}_2\text{CO}_3$ for spodumene-based production, identifying energy and chemical inputs as key contributors. Similar trends are reported by

Table 1

Materials and energy required to produce 1 kg of Li_2CO_3 under different foreground scenario cases for each process route. Detailed LCIs for each case are provided in SI-1 (Tables S7–S9), where materials, energy, waste, and emissions, including impurities and contaminants in waste streams, are reported separately for each process stage.

Material and energy flows	Unit	Low-performance case			Baseline/base case			Optimised case		
		Route A	Route B	Route C	Route A	Route B	Route C	Route A	Route B	Route C
Inputs										
Spodumene ore (Li grade: 3.12%)	kg	11.7	21.1	30.2	8.16	14.7	21	7.12	12.8	18.3
Sodium carbonate	kg	3.52	6.34	9.06	1.91	3.44	4.91	0.71	1.27	1.81
CO ₂ liquid	kg	2.63	4.73	6.76	1.73	3.12	4.46	1.35	2.42	3.46
Magnesium oxide	kg	0.95	n.a.	n.a.	0.66	n.a.	n.a.	0.57	n.a.	n.a.
Sodium hydroxide	kg	13.1	n.a.	n.a.	9.08	n.a.	n.a.	7.92	n.a.	n.a.
Deionised water	kg	141	330	362	93.7	244	239	73	207	186
Tap water	kg	n.a.	22.9	n.a.	n.a.	15.1	n.a.	n.a.	11.7	n.a.
Electricity	kWh	40.2	71	100	27.1	47.4	66.8	21.4	37.3	52.2
Heat	MJ	21.4	98.9	53.4	14.1	71	35.3	11	58.9	27.4
Outputs										
Battery-grade Li ₂ CO ₃	kg	1	1	1	1	1	1	1	1	1
CO ₂ emissions	kg	2.9	5.21	7.45	1.88	3.38	4.83	1.4	2.51	3.59
Solid waste	kg	25.6	43.8	59.3	8.05	13.5	18.5	13.4	22.5	30.4
Water vapor	kg	33.8	322	78.8	22.8	237	52.4	n.a.	n.a.	n.a.

n.a.: not applicable; the flow is not present in the process scenario case or is fully recirculated (e.g., water vapour).

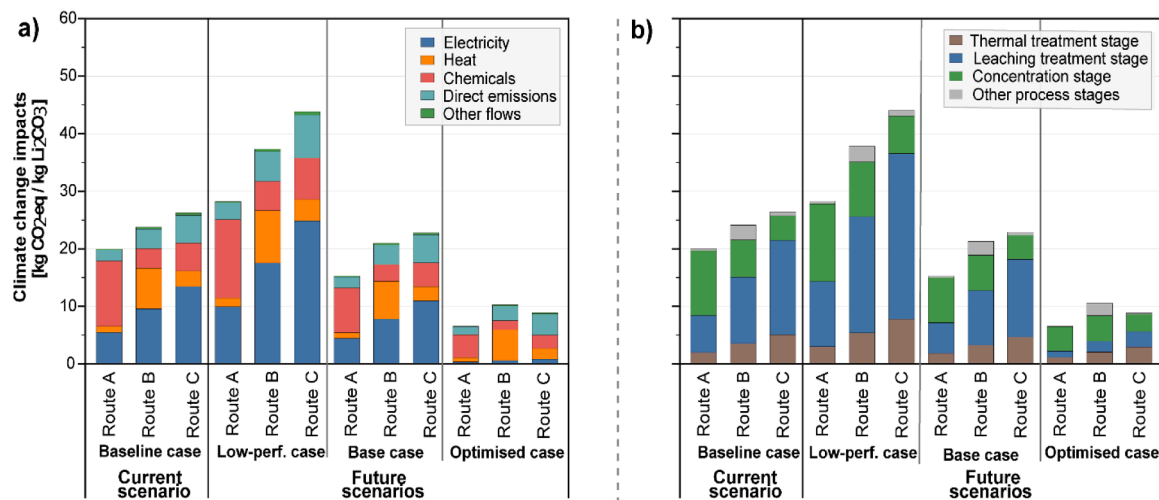


Fig. 3. Climate change impacts for each production route under current and future scenario cases, disaggregated by (a) contributing process flows and (b) contributing process stages.

Jiang et al. (2020), Mas-Fons et al. (2024) and Lappalainen et al. (2025), with impact intensities varying with feed characteristics (e.g., ore quality), technology maturity (TRL), foreground modelling data (e.g., estimation approach and assumptions), background system choices (e.g., energy sources), geographical scope (e.g., electricity mix), and other methodological assumptions.

A multi-category comparison reveals clear differences among the routes when expressed relative to the Route A baseline (set at 100%). As shown in Fig. 4a, Routes B and C generally perform worse under current conditions in almost all categories, with CC impacts larger by 19% and 32%, respectively. Only EUFT (46% and 53%) and PM (84% and 92%) show an opposite pattern. The largest differences appear for dissipation (JRC-LCI), with RC-LCI increasing to 225–272%. These increases are associated with Li that potentially dissipates during the concentration stage. Overall, while Routes B and C offer improvements in a few categories, their environmental performance remains generally lower than that of Route A under current conditions.

3.3.2. Future scenario cases

Future scenario cases indicate substantial variations in impacts across all routes, while hotspot patterns shift. As shown in Fig. 3, the low-performance case, representing the most unfavourable foreground

combinations, leads to CC impacts increasing to 28.2, 37.3, and 43.8 kg $\text{CO}_2\text{-eq}$ for Routes A, B, and C, corresponding to rises of approximately 41.5%, 57.3%, and 67 % relative to the baseline. This reflects, in particular, the effect of lower Li recovery efficiencies. In the future base case, impacts decrease to 15.2, 20.9, and 22.8 kg $\text{CO}_2\text{-eq}$ for Routes A, B and C, respectively, while they fall further to 6.6, 10.3, and 8.8 kg $\text{CO}_2\text{-eq}$ in the optimised case. Compared with the conventional route value of ~ 20.4 kg $\text{CO}_2\text{-eq/kg Li}_2\text{CO}_3$ reported by Kelly et al. (2021), the base case achieves a reduction of up to ~ 26 % (Route A), while the optimised case achieves a much larger reduction of approximately 50–68%. The low-performance case exceeds this reference across all routes, while in the base case only Route A falls below it. In Route A, NaOH used in the concentration stage remains the dominant contributor to CC impacts while electricity contributions decline, particularly in the base and optimised cases. In Route B, the leaching stage dominates in the low-performance and base cases. In the optimised case, hotspots shift toward the concentration stage, with heat becoming the primary contributor. In Route C, the leaching stage remains dominant in the low-performance and base cases, while in the optimised case, the concentration stage becomes the main contributor to CC impacts, with direct emissions emerging as the major hotspot. Across future scenarios (Fig. 4a), low-performance cases increase impacts, whereas base and

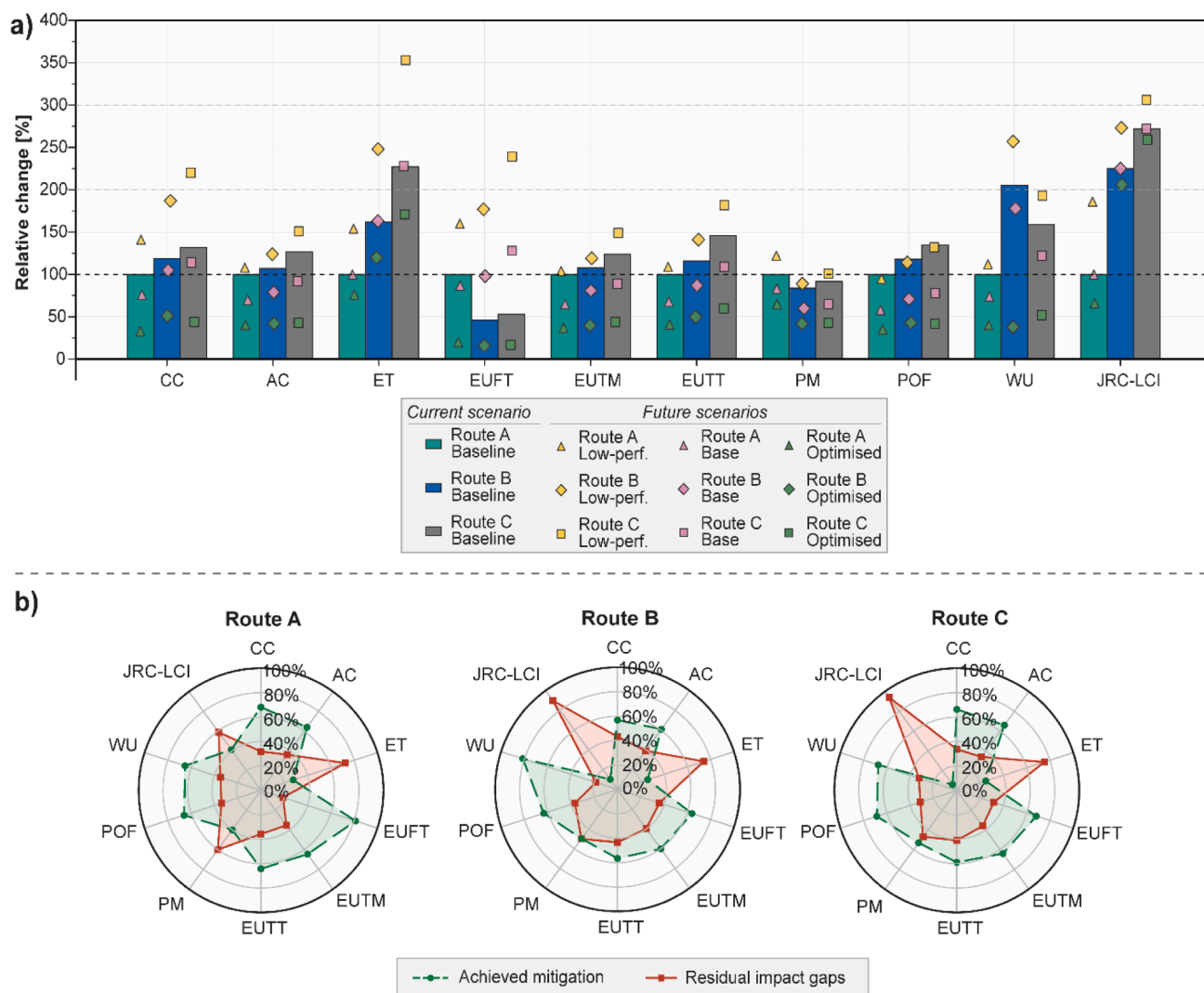


Fig. 4. (a) Environmental impact intensity comparisons relative to Route A baseline case (current scenario) across process routes under current and future scenarios; (b) potential mitigation achieved (relative impact reduction) and residual impact gaps (remaining differences after reduction) across the three process routes from baseline to future optimised scenarios.

optimised cases consistently reduce them.

These impact patterns reflect the combined influence of the underlying considerations, particularly in the background system. At the same time, these follow the defined scenario narratives and adopted combinations, while foreground and background developments may evolve independently, potentially leading to alternative impact trajectories. Future scenarios under ambitious decarbonisation pathways demonstrate a notable reduction in impacts across all process routes, particularly in the optimised cases, driven by electricity mixes with high shares of renewables and partial electrification of process heat. On the other hand, process emissions remain largely unchanged, as scenario transformations primarily target the background system. Chemical production shows strong mitigation potential through significant improvements in energy use enabled by decarbonised energy inputs, while background direct emissions remain less responsive. These contrasting background-system pathways associated with SSP combinations drive the observed variations. These findings can be aligned with current decarbonisation roadmaps, indicating limited mitigation prospects for scope 1 emissions (Antonini et al., 2025; Istrate et al., 2024), consistent with the time horizon considered in this study. Overall, mitigation potentials differ across impact categories (Fig. 4b). Background-system changes mainly reduce CC, EUFT, EUTM, and EUTT, whereas PM, ET, and JRC-LCI are more sensitive to foreground improvements such as

dust control, recovery efficiency, and waste impurity management. ET and JRC-LCI show limited sensitivity to background changes (0–6%) but higher mitigation under foreground improvements (up to ~25–41%), as reflected in the scenario results (Fig. 4b and SI-1). In particular, JRC-LCI is mainly associated with Li losses and recovery efficiency, with Li overall recovery in Route A increasing from ~51% to ~85% across scenarios, while ET is influenced by impurity management and residue generation. PM shows comparable sensitivity to both foreground and background changes (~26–32%). Impact-category-specific mitigation strategies are therefore required, aligned with the dominant drivers of each impact category. Further detailed results are provided in Appendix A (Fig. A1 and Fig. A2) and Appendix B.

3.4. Implications of key varying factors and uncertainty propagation

Sensitivity results show that foreground variations induced by operational ranges of process parameters lead to moderate shifts across all impact categories (Fig. 5a). For the baseline case, CC impacts vary from –24% to +29% across all routes, while the low-performance (–25% to +30%) and base cases (–23% to +28%) follow similar patterns. Under the optimised case, CC sensitivity narrows, with impacts ranging from –17% to +22% across all routes. Overall, EUFT shows the highest sensitivity, whereas ET displays the lowest sensitivity. Under the

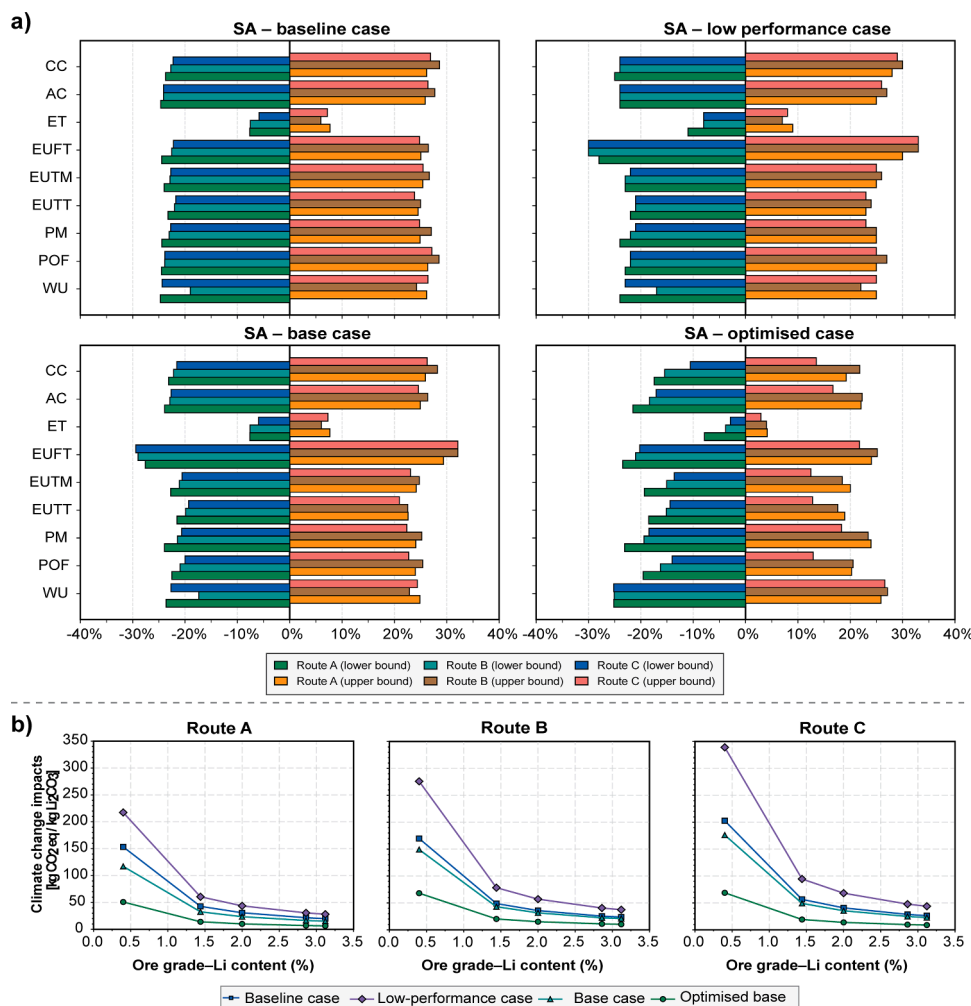


Fig. 5. Sensitivity analysis results based on the implications of key varying parameters: (a) relative impact changes between lower- and upper-bound cases; (b) potential variation in climate change impacts induced by ore grade quality.

baseline case, CC impacts rise from about 20–26 kg CO₂-eq/kg Li₂CO₃ at 3.12% Li to roughly 153–203 kg CO₂-eq/kg Li₂CO₃ at 0.4% Li across Routes A–C, i.e. an increase by a factor of approximately 8 (Fig. 5b). This is clearly associated with the higher energy and materials requirements needed to recover the same quantity of lithium carbonate from lower-quality feedstock. The relationship between ore grade and impact intensity is approximately inverse. These findings highlight the non-linear nature of resource efficiency, a key consideration as future lithium supply will increasingly rely on lower-grade ores. When paired with improved future scenarios, the CC impacts associated with low-grade feedstocks could be reduced by more than half across all routes, with CC impacts at 0.4% Li decreasing from 153–203 kg CO₂-eq in the current baseline to about 51–69 kg CO₂-eq in the optimised case. Full impact category-level results for other impact categories are reported in SI-2. In addition, Monte Carlo analysis for the best-performing case (Route A, optimised; see SI-1, Table S20) confirms that key hotspots and overall trends remain stable under uncertainty. Variability is generally moderate, with CC showing a standard deviation of ~4–5%. Similar patterns were observed across the other impact categories, and variability generally remained below 10%. These ranges remain within the bounds indicated by the sensitivity analysis, supporting the robustness of the main conclusions. The same uncertainty framework can be extended to the other process scenario cases.

3.5. Implications and relevance of eco-design strategies

Eco-design development was initiated by comparing alternative process configurations and examining key process parameters, supported by sensitivity and uncertainty analyses to capture further process variability. The observed improvements across scenario cases reflected performance gains achievable through the proposed process optimisation and operational refinement based on current insights and adopted scenario-based modelling assumptions. This indicated that environmental improvements follow a constrained progression, primarily driven by decarbonised systems, efficiency gains and resource recirculation, while further improvements can also be induced by fundamental changes in process design and system integration. Across the transition from the baseline cases to the optimised cases, Route A consistently emerged as the most promising configuration across most impact categories. The results demonstrated how coordinated FG and BG interventions can guide prospective eco-design priorities. For Route A, CC impacts are reduced by 21% with FG improvements alone and by 60% with BG improvements alone, increasing to a 68% reduction when FG and BG interventions are combined. The highest FG-only mitigation (41%) is observed for WU and JRC-LCI. When FG and BG measures are combined, the largest reductions are achieved for EUFT (81%), while ET remains the least responsive category (28%) (Fig. 4b). Full results on FG- and BG-based mitigation achieved and remaining impact gaps, assessed separately and in combination, are provided in SI-1. These results should be interpreted in light of the underlying modelling considerations and

the adopted scenario rationale. At the same time, different trade-offs become more pronounced as environmental hotspots shift under scale-up and optimised conditions. For instance, although the best-performing case (Route A, optimised case) improves lithium recovery and reduces ore demand and overall climate change impacts, the higher process efficiency also requires additional chemicals (particularly NaOH, representing ~65–75% of the total chemical inputs across the Route A scenarios; Table 1) and further process integration related to impurity removal. In parallel, under decarbonised background systems, the relative contribution of direct process emissions becomes more pronounced, increasing from ~9% in the baseline case to ~21% of total climate change impacts in the optimised Route A scenario, highlighting the growing importance of direct emission abatement strategies under future low-carbon systems. From a practical perspective, these trade-offs also influence process design, operational complexity costs, and industrial-scale feasibility, including equipment selection, reactor design, and overall process configuration.

3.5.1. Resource and energy-efficiency potentials

The analysis showed that resource efficiency, covering minerals, chemicals, water resources, and energy inputs, is mainly driven by process performance (overall Li recovery) and feed quality (ore grade). These two factors, therefore, remain the core focus of this eco-design pillar. Although Routes B and C require fewer chemical inputs, their lower lithium recovery results in higher Li losses and reduced Li accessibility, an issue that becomes more critical for low-grade ores, which are harder to process and are expected to dominate future supply. Integrating pre-concentration steps such as flotation before chemical treatments could therefore strengthen the recovery of low-grade ores and support more sustainable configurations. Conventional routes often include such steps, which show high feasibility and could also be integrated in future development for low-grade feed, although such a process configuration and integration may require additional chemical and energy inputs.

Regarding energy efficiency, reducing thermal energy demand is essential. This can be achieved through thermal integration and residual heat recovery. This is particularly relevant in evaporative crystallisation and drying, where multi-effect evaporation and multi-stage drying were explored as higher-efficiency alternatives to conventional single-stage systems, which typically release large amounts of unused heat. These options were assessed in the LCA models using literature-based energy proxies from similar processes due to limited operational data, while still enabling early-stage consideration for thermal energy-efficient integration in the process configurations. Such technologies already show high operational maturity and practical large-scale deployment. Further heat-integration improvements, including electrification, could be implemented in drying and calcination furnaces (Harvey et al., 2022). For instance, heat losses from calcination could be recovered to preheat the leaching solution, lowering overall heat demand. Rotary kilns used for calcination can lose a significant fraction of their input heat (Atmaca and Yumrutaş, 2014), highlighting the importance and feasibility of waste-heat recovery as a key optimisation strategy.

3.5.2. Process circularity pathways

Recirculation and regeneration of process flows are essential for tackling impact categories sensitive to changes in the foreground system. Na_2CO_3 and water-vapour streams show notable potential for recirculation and regeneration. The results also indicate that NaOH remains a dominant hotspot under both current and future conditions. Even under intensified decarbonisation, NaOH production continues to be a major burden. At the same time, electricity is the primary contributor under current conditions in the production of NaOH; decarbonising electricity shifts the hotspot burdens toward other process flows, such as heat inputs and quicklime, which are less decarbonised and associated with hard-to-abate emissions. From a process perspective, these trade-offs are closely conditioned by process design choices

and system integration, particularly in the leaching and concentration stages. For instance, CO_2 demand also depends on reactor design and behaviour under supercritical conditions, while system integration can impose additional constraints. These constraints directly influence not only environmental performance, but also operational complexity, the feasibility of reagent recovery and water recirculation, and may involve further compromises and operational concerns. Material selection and substitution strategies can also support further mitigation. The CO_2 -based supercritical leaching approach (COOL+) applied in this study substitutes conventional sulphuric-acid leaching, reducing the use of strong acids. Na_2CO_3 was partially recovered and recirculated for reuse. Similar regenerative strategies could be extended to other reagents and waste streams, contributing to broader zero-waste objectives. Considering these insights, future work should extend regenerative and substitution strategies to other key chemicals, including NaOH, given its strong influence on impact intensities. For instance, the use of NaOH could be avoided or substituted, depending on leachate conditions, by alternative reagents such as calcium oxide combined with a magnesium (II) source for impurity removal. In addition, carbonated water can also substitute deionised water. These substitution strategies would require further assessment to evaluate their environmental performance.

Overall, circular strategies such as reagent regeneration, internal water-loop closure, and residue valorisation, consistent with recommendations by Binnemans and Jones (2023), represent practically feasible options at different levels for reducing long-term impacts and dependence on virgin inputs while strengthening zero-waste pathways. These trade-offs highlight the need to evaluate process configurations not only from an environmental perspective but also in terms of techno-economic feasibility, particularly at higher TRLs (e.g., industrial scale), where system robustness, integration, and material availability become critical.

3.5.3. Decarbonisation prospects

Energy-related hotspots were particularly addressed through the defined future background scenarios, which consider the use of low-carbon energy sources consistent with expected transitions in energy systems under climate policies and frameworks. While decarbonisation shows limited benefits for certain impact categories, such as ET, broad decarbonisation of energy remains the eco-design pillar with the highest mitigation potential and high feasibility for most of the impact categories. Decarbonising energy provision alone reduces climate change impacts by more than 50%. At the same time, direct emissions remain among the most difficult to abate due to the techno-economic challenges associated with mitigation options for scope 1 emissions, such as carbon capture, utilisation, and storage (CCUS) (Antonini et al., 2025). In addition, the decarbonisation potential for chemical production in the background system is also limited, as highlighted for sodium hydroxide and other reagents, where process-related emissions persist even under cleaner energy inputs (Istrate et al., 2024). Additional mitigation potential for thermal treatment operations can be achieved through heat decarbonisation, building on electrification in the near term and the longer-term deployment of green hydrogen and renewable fuels (Antonini et al., 2025), for instance, through the use of electric furnaces for calcination. This indicates that further efforts should be directed toward innovating technologies capable of reducing on-site (scope 1) emissions and improving the carbon performance of key reagents used in lithium production.

3.6. Future perspectives

The results indicate that environmental performance depends on key process elements and may shift strongly under future operating conditions, highlighting the need for improved data quality through higher-TRL deployment (TRL 7–9) and continuous monitoring. These findings remain subject to data limitations that are unavoidable at an early stage of development (mid-TRL) and necessarily need scale-up assumptions.

This may further affect modelling results and impact magnitudes under industrial conditions and should be refined progressively as more advanced process data become available. Such improvements will, in turn, enable more robust comparisons with global conventional lithium production route datasets, such as those reported in Lai et al. (2026), equally affected by data uncertainty and subject to continuous variations within a given range. Future work should prioritise the eco-design prospects identified, particularly for the best-performing process configuration. Advancing to higher-TRL through pilot and demonstration-scale deployment supported by process simulation and industrial expertise will be key to further reduce uncertainty. On-site waste valorisation, such as the use of solid residues in construction materials (e.g., ceramics production), can generate environmental benefits and enhance circularity, consistent with previous studies (Adrianto and Pfister, 2022; Beylot et al., 2022). Considering different waste-modelling approaches can also improve the representation of associated waste-related impacts (Muller et al., 2022). Finally, extending dissipation analysis to other minerals in the feed, alongside economic value and long-term implications for resource accessibility using alternative dissipation methods (Ardente et al., 2023; Beylot et al., 2024) would provide a more complete understanding of considerations related to mineral resource value and associated loss of accessibility.

4. Conclusions

This study evaluated the potential environmental performance of a novel battery-grade lithium carbonate production process under different configurations and scenarios, demonstrating the value of applying life-cycle thinking early in technology development. The results reveal key trade-offs and shifting hotspots under future conditions, providing a foundation for targeted eco-design improvements in the foreground and background systems.

Substantial reduction potentials are achieved under future scenarios, particularly through background energy decarbonisation. However, decarbonised energy alone cannot mitigate certain impact potentials, highlighting the importance of complementing energy decarbonisation with resource- and energy-efficiency measures, and circularity strategies toward broad net-zero waste and emissions. For the best-performing route, climate-change impacts decrease by ~60% through background decarbonisation alone, and by up to ~68% when combined with foreground improvements, decreasing from 20 to 6.6 kg CO₂-eq kg⁻¹ Li₂CO₃. This process route achieves an average potential reduction of ~58% across all impact categories. Overall, environmental-impact variability is driven by ore grade, lithium-recovery efficiency, and recirculation

potential. In a forward-looking context, targeted optimisation of the key hotspots identified and explored in this study can enable substantial environmental gains and support alignment with long-term sustainability ambitions.

CRediT authorship contribution statement

Gyslain Ngadi Sakatadi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antoine Beylot:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Frédéric Lai:** Writing – review & editing, Methodology, Conceptualization. **Sebastian Hippmann:** Writing – review & editing, Investigation, Formal analysis. **Sandra Pavón:** Writing – review & editing, Investigation, Formal analysis. **Gian Andrea Blengini:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

■ Gyslain Ngadi Sakatadi, Sebastian Hippmann, Sandra Pavón, and Gian Andrea Blengini acknowledge funding from the European Union within the project METALLICO (Grant agreement no. 101091682)

■ Antoine Beylot acknowledges funding from the French State managed by the National Research Agency under France 2030 bearing the reference ANR-22-EXSS-0007

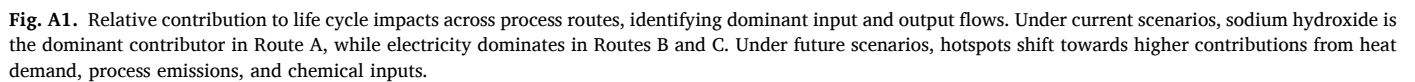
■ Gyslain Ngadi Sakatadi and Gian Andrea Blengini acknowledge funding from the NODES project under the MUR – PNRR M4C2 1.5, funded by the European Union – Next Generation EU (Grant Agreement no. ECS00000036)

Special thanks are extended to the Horizon Europe METALLICO project team at Politecnico di Torino, Stefano Antonini, Giulia Pezzin, Giulia Grisolia, and Isabella Bianco, for their initial insights and contributions to the development and definition of the sustainability assessment procedure applied to mid- to low-TRL battery metals recovery technologies. The authors also thank all METALLICO project partners and experts for their valuable insights and for providing experimental test data that supported the definition and validation of the inventories, estimations, and assumptions used in this study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2026.109179](https://doi.org/10.1016/j.resconrec.2026.109179).

Appendix A. Extended results



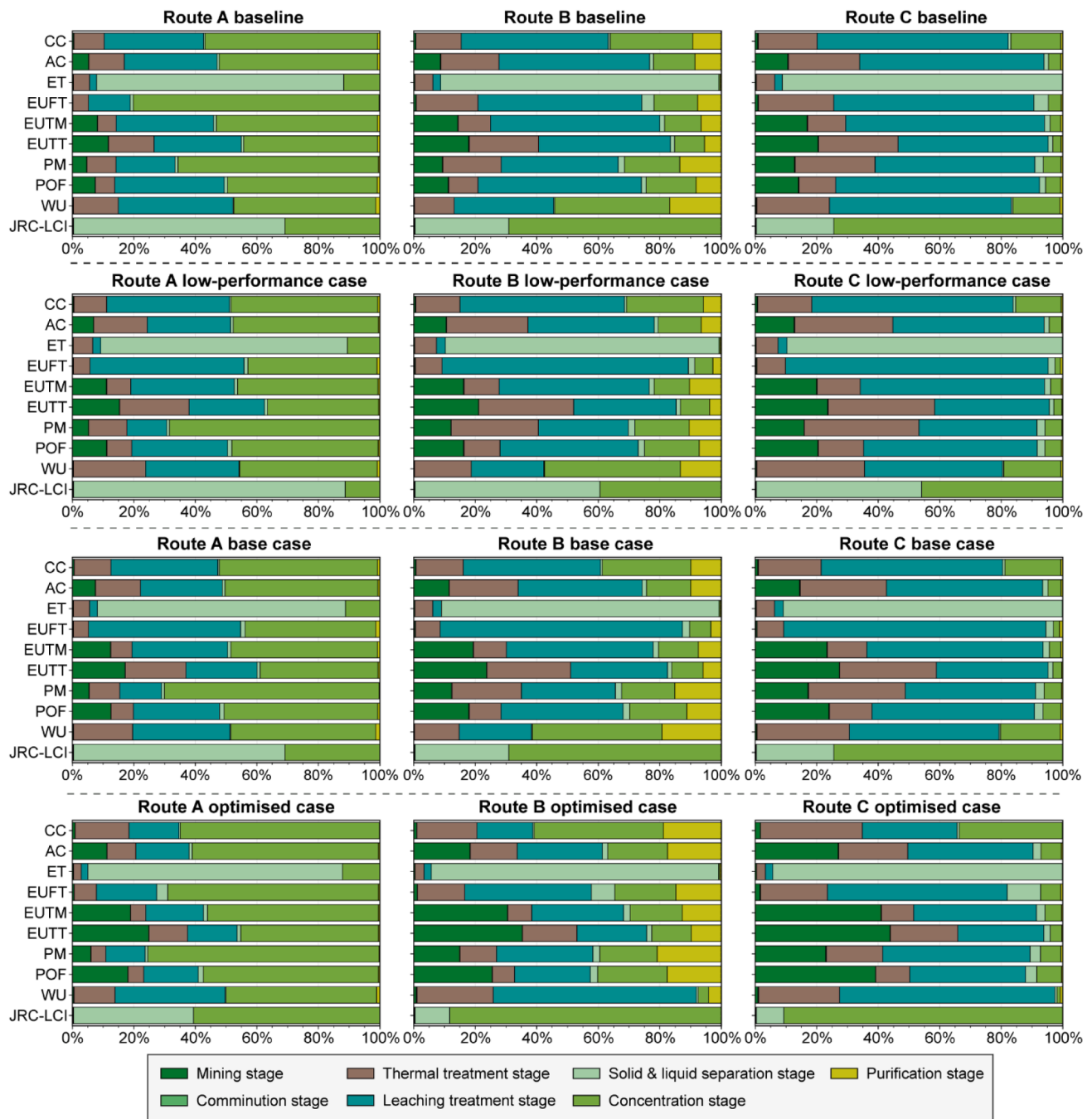


Fig. A2. Relative contribution to life cycle impacts across process routes. Under both current and future scenarios, the leaching and concentration stages are the dominant contributors to most impact categories.

Appendix B. Supplementary information (SI)

- SI-1. Modelling approach, data estimation, disaggregated life cycle inventories, and additional results figures
- SI-2. Scenario-case exportable inventories in Activity Browser / Brightway2 formats and full sets of environmental impact results

Data availability

All data used in the LCA models are provided in the Supplementary Information. Raw experimental data are available upon reasonable request.

References

- Adrianto, L.R., Pfister, S., 2022. Prospective environmental assessment of reprocessing and valorization alternatives for sulfidic copper tailings. *Resour. Conserv. Recycl.* 186, 106567. <https://doi.org/10.1016/j.resconrec.2022.106567>.

- Al-Karaghoul, A., Kazmerski, L.L., 2013. Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renew. Sustain. Energy Rev.* 24, 343–356. <https://doi.org/10.1016/j.rser.2012.12.064>.
- Antonini, S., Grisolia, G., Blengini, G.A., 2025. Three open questions on Net Zero in the mining and metals industries. *Miner. Econ.* <https://doi.org/10.1007/s13563-025-00554-2>.
- Ardente, F., Beylot, A., Zampori, L., 2023. A price-based life cycle impact assessment method to quantify the reduced accessibility to mineral resources value. *Int. J. Life Cycle Assess.* 28, 95–109. <https://doi.org/10.1007/s11367-022-02102-4>.
- Arvidsson, R., Svanström, M., Sandén, B.A., Thonemann, N., Steubing, B., Cucurachi, S., 2024. Terminology for future-oriented life cycle assessment: review and recommendations. *Int. J. Life Cycle Assess.* 29, 607–613. <https://doi.org/10.1007/s11367-023-02265-8>.
- Arvidsson, R., Tillman, A., Sandén, B.A., Janssen, M., Nordelöf, A., Kushnir, D., Molander, S., 2018. Environmental assessment of emerging technologies: recommendations for prospective LCA. *J. Ind. Ecol.* 22, 1286–1294. <https://doi.org/10.1111/jiec.12690>.
- Ashraf, H.M., Al-Sobhi, S.A., Abdelrahman, M., 2026. Integration of life cycle sustainability assessment and process simulation to achieve an eco-design in linear alpha olefin (LAO) plant. *J. Clean. Prod.* 544, 147619. <https://doi.org/10.1016/j.jclepro.2026.147619>.
- Atmaca, A., Yumrutaş, R., 2014. Analysis of the parameters affecting energy consumption of a rotary kiln in cement industry. *Appl. Therm. Eng.* 66, 435–444. <https://doi.org/10.1016/j.applthermaleng.2014.02.038>.
- Beylot, A., Ardente, F., Sala, S., Zampori, L., 2020. Accounting for the dissipation of abiotic resources in LCA: Status, key challenges and potential way forward. *Resour. Conserv. Recycl.* 157, 104748. <https://doi.org/10.1016/j.resconrec.2020.104748>.
- Beylot, A., Ardente, F., Sala, S., Zampori, L., 2021a. Mineral resource dissipation in life cycle inventories. *Int. J. Life Cycle Assess.* <https://doi.org/10.1007/s11367-021-01875-4>.
- Beylot, A., Bodénan, F., Guezennec, A.-G., Muller, S., 2022. LCA as a support to more sustainable tailings management: critical review, lessons learnt and potential way forward. *Resour. Conserv. Recycl.* 183, 106347. <https://doi.org/10.1016/j.resconrec.2022.106347>.
- Beylot, A., Dewulf, J., Greffe, T., Muller, S., Blengini, G.-A., 2024. Mineral resources depletion, dissipation and accessibility in LCA: a critical analysis. *Int. J. Life Cycle Assess.* 29, 890–908. <https://doi.org/10.1007/s11367-023-02278-3>.
- Beylot, A., Muller, S., Segura-Salazar, J., Brito-Parada, P., Paneri, A., Yan, X., Lai, F., Roethe, R., Thomas, G., Goettmann, F., Braun, M., Moradi, S., Fitzpatrick, R., Moore, K., Bodin, J., 2021b. Switch on-switch off small-scale mining: Environmental performance in a life cycle perspective. *J. Clean. Prod.* 312, 127647. <https://doi.org/10.1016/j.jclepro.2021.127647>.
- Binnemans, J., Jones, P.T., 2023. The twelve principles of circular hydrometallurgy. *J. Sustain. Metall.* 9, 1–25. <https://doi.org/10.1007/s40831-022-00636-3>.
- Buyle, M., Audenaert, A., Billen, P., Boonen, K., Van Passel, S., 2019. The future of Ex-Ante LCA? Lessons Learned. *Pract. Recommendation. Sustain.* 11, 5456. <https://doi.org/10.3390/su11195456>.
- Caduff, M., Huijbregts, M.A.J., Althaus, H.-J., Hendriks, A.J., 2011. Power-law relationships for estimating mass, fuel consumption and costs of energy conversion equipments. *Environ. Sci. Technol.* 45, 751–754. <https://doi.org/10.1021/es103095k>.
- Chordia, M., Wickerts, S., Nordelöf, A., Arvidsson, R., 2022. Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene. *Resour. Conserv. Recycl.* 187, 106634. <https://doi.org/10.1016/j.resconrec.2022.106634>.
- Dahlkamp, J.M., Quintero, C., Videla, A., Rojas, R., 2024. Production processes for LiOH – a review. *Hydrometallurgy* 223, 106217. <https://doi.org/10.1016/j.hydromet.2023.106217>.
- European Commission. Joint Research Centre, Gonzalez Torres, M., Kouloumpis, V., Rodriguez Manotas, J., Magrini, C., Senatore, V., Napolano, L., Eynard, U., Ardente, F., Gama Caldas, M., 2025. Developing a method for the assessment of life cycle environmental impacts of products, and integration in or relation with the methodology for the ecodesign of energy related products, EUR. Publications Office of the European Union, LU. <https://doi.org/10.2760/3515898>.
- European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Grohol, M., Veeh, C., 2023. Study on the critical raw materials for the EU 2023: final report. *Publicat. Office of the Europ. Union*. <https://data.europa.eu/doi/10.2873/725585>.
- Chapter 3 - size reduction and energy requirement. In: Gupta, A., Yan, D. (Eds.), 2016. *Mineral Processing Design and Operations (Second Edition)*. Elsevier, Amsterdam, pp. 71–121. <https://doi.org/10.1016/B978-0-444-63589-1.00003-4>.
- Hansel, B., Rogoll, C., Ebert, D., Möckel, R., Pätzold, C., Bertau, M., 2026. Early-stage recovery of lithium from lithium-ion battery black mass in pilot scale using supercritical CO₂. *ACS Sustain. Resour. Manag. Accusresmtg*, 5c00663. <https://doi.org/10.1021/acssusresmtg.5c00663>.
- Harppecht, C., Miranda Xicotencatl, B., Van Nielen, S., Van Der Meide, M., Li, C., Li, Z., Tukker, A., Steubing, B., 2024. Future environmental impacts of metals: a systematic review of impact trends, modelling approaches, and challenges. *Resour. Conserv. Recycl.* 205, 107572. <https://doi.org/10.1016/j.resconrec.2024.107572>.
- Harvey, J.-P., Courchesne, W., Vo, M.D., Oishi, K., Robelin, C., Mahue, U., Leclerc, P., Al-Haik, A., 2022. Greener reactants, renewable energies and environmental impact mitigation strategies in pyrometallurgical processes: a review. *MRS Energ. Sustain.* 9, 212–247. <https://doi.org/10.1557/s43581-022-00042-y>.
- Hund, K., La Porta, D., Fabregas, T.P., Laing, T., Drexhage, 2020. *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*. World Bank. URL. <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/en/099052423172525564>. accessed 4.18.25.
- IEA, 2021. The role of critical minerals in clean energy transitions. <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions>.
- ISO, 2006a. ISO 14040:2006 environmental management - life cycle assessment - principles and framework. ISO 14040. URL. <https://www.iso.org/standard/37456.html>. accessed 4.19.25.
- ISO, 2006b. ISO 14044:2006 environmental management - life cycle assessment - requirements and guidelines. ISO 14044. URL. <https://www.iso.org/standard/38498.html>. accessed 4.19.25.
- Istrate, R., Mas-Fons, A., Beylot, A., Northey, S., Vaidya, K., Sonnemann, G., Kleijn, R., Steubing, B., 2024. Decarbonizing lithium-ion battery primary raw materials supply chain. *Joule* 8, 2992–3016. <https://doi.org/10.1016/j.joule.2024.10.003>.
- Iyer, R.K., Kelly, J.C., Wang, M., 2026. Life-cycle greenhouse gas emissions analysis of battery-grade lithium production in Finland. *Resour. Conserv. Recycl.* 225, 108592. <https://doi.org/10.1016/j.resconrec.2025.108592>.
- Jiang, S., Zhang, L., Li, F., Hua, H., Liu, X., Yuan, Z., Wu, H., 2020. Environmental impacts of lithium production showing the importance of primary data of upstream process in life-cycle assessment. *J. Environ. Manage.* 262, 110253. <https://doi.org/10.1016/j.jenvman.2020.110253>.
- Kelly, J.C., Wang, M., Dai, Q., Winjobi, O., 2021. Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. *Resour. Conserv. Recycl.* 174, 105762. <https://doi.org/10.1016/j.resconrec.2021.105762>.
- Khakmardan, S., Crawford, R.H., Giurco, D., Li, W., 2025. Constructing a life cycle inventory of Spodumene concentrate production: Greenbushes case. *Western Australia. J. Clean. Prod.* 496, 145123. <https://doi.org/10.1016/j.jclepro.2025.145123>.
- Lai, F., Beylot, A., Navarro, R., Schimek, P., Hartlieb, P., Johansson, D., Segarra, P., Amor, C., Villeneuve, J., 2021. The environmental performance of mining operations: comparison of alternative mining solutions in a life cycle perspective. *J. Clean. Prod.* 315, 128030. <https://doi.org/10.1016/j.jclepro.2021.128030>.
- Lai, F., Muller, S., Philippe, A., Istrate, R., Xicotencatl, B.M., Aski, A.M., Fons, A.M., Segura-Salazar, J., Saldivar, J.S., Cimprich, A., Northey, S., Lima, L.D.S., Boone, L., Yokoi, R., Islam, K., Paschalidou, I., Cerdas, F., Balboa-Espinoza, V., Koyamparambath, A., Hennioui, D., Collignon, V., Reys, A., Sakatadi, G.N., Dewulf, J., Steubing, B., Helbig, C., Lefebvre, G., Blengini, G.A., Superti, V., Motoshita, M., Sonnemann, G., Awuah-Offei, K., Young, S.B., Murakami, S., Beylot, A., 2026. Life cycle inventories of global metal and mineral supply chains: a comprehensive data review, analysis and processing. *Resour. Conserv. Recycl.* 226, 108709. <https://doi.org/10.1016/j.resconrec.2025.108709>.
- Langkau, S., Steubing, B., Mutel, C., Ajie, M.P., Erdmann, L., Voglhuber-Slavinsky, A., Janssen, M., 2023. A stepwise approach for scenario-based inventory modelling for prospective LCA (SIMPL). *Int. J. Life Cycle Assess.* 28, 1169–1193. <https://doi.org/10.1007/s11367-023-02175-9>.
- Lappalainen, H., Elomaa, H., Aromaa, J., Lundström, M., 2025. Life cycle assessment of ore-based lithium carbonate production using sulfuric acid roasting and soda leaching: Impact of sodium sulfate electro dialysis. *Hydrometallurgy* 233, 106450. <https://doi.org/10.1016/j.hydromet.2025.106450>.
- Lappalainen, H., Rinne, M., Elomaa, H., Aromaa, J., Lundström, M., 2024. Environmental impacts of lithium hydroxide monohydrate production from spodumene concentrate – A simulation-based life cycle assessment. *Miner. Eng.* 209, 108632. <https://doi.org/10.1016/j.mineng.2024.108632>.
- Liu, T., Gu, Y., Hu, G., Wu, Y., Yuan, Q., Hu, H., Zuo, T., 2026. Lifecycle eco-design potential of battery electric vehicles considering environmental and economic functions. *Resour. Conserv. Recycl.* 224, 108546. <https://doi.org/10.1016/j.resconrec.2025.108546>.
- Mas-Fons, A., Horta Arduin, R., Loubet, P., Pereira, T., Parvez, A.M., Sonnemann, G., 2024. Carbon and water footprint of battery-grade lithium from brine and spodumene: a simulation-based LCA. *J. Clean. Prod.* 452, 142108. <https://doi.org/10.1016/j.jclepro.2024.142108>.
- Mende, R., Kaiser, D., Pavón, S., Bertau, M., 2023. The COOL process: a holistic approach towards lithium recycling. *Waste Biomass Valorizat.* 14, 3027–3042. <https://doi.org/10.1007/s12649-023-02043-5>.
- Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D.P., Font Vivanco, D., Deetman, S., Edelenbosch, O.Y., Guinée, J., Tukker, A.P., 2020. When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment. *J. Ind. Ecol.* 24, 64–79. <https://doi.org/10.1111/jiec.12825>.
- Meng, F., McNeice, J., Zadeh, S.S., Ghahreman, A., 2021. Review of lithium production and recovery from minerals, brines, and lithium-ion batteries. *Miner. Process. Extr. Metall. Rev.* 42, 123–141. <https://doi.org/10.1080/08827508.2019.1668387>.
- Moni, S.M., Mahmud, R., High, K., Carbajales-Dale, M., 2020. Life cycle assessment of emerging technologies: a review. *J. Ind. Ecol.* 24, 52–63. <https://doi.org/10.1111/jiec.12965>.
- Muller, S., Lassin, A., Lai, F., Thiéry, D., Guignot, S., 2022. Modelling releases from tailings in life cycle assessments of the mining sector: from generic models to reactive transport modelling. *Miner. Eng.* 180, 107481. <https://doi.org/10.1016/j.mineng.2022.107481>.
- Muller, S., Lesage, P., Samson, R., 2016. Giving a scientific basis for uncertainty factors used in global life cycle inventory databases: an algorithm to update factors using new information. *Int. J. Life Cycle Assess.* 21, 1185–1196. <https://doi.org/10.1007/s11367-016-1098-5>.
- Mutel, C., 2017. Brightway: an open source framework for life cycle assessment. *J. Open Source Softw.* 2, 236. <https://doi.org/10.21105/joss.00236>.

- Ndlovu, P., Chabalala, M.B., Rampou, M., Khumalo, S.P.-G., Fashu, S., Hungwe, D., 2025. Carbon dioxide utilization in mineral processing. *J. CO₂ Util.* 94, 103063. <https://doi.org/10.1016/j.jcou.2025.103063>.
- Nikfar, S., Fahimi, A., Vahidi, E., 2025. Unlocking sustainable lithium: a comparative life cycle assessment of innovative extraction methods from brine. *Resour. Conserv. Recycl.* 212, 107977. <https://doi.org/10.1016/j.resconrec.2024.107977>.
- Nishikawa, E., Sleep, S., Bergerson, J., 2026. Life cycle carbon footprint of novel technologies for lithium production and potential implications for the supply chain in North America. *Resour. Conserv. Recycl.* 225, 108598. <https://doi.org/10.1016/j.resconrec.2025.108598>.
- Nuss, P., Eckelman, M.J., 2014. Life cycle assessment of metals: a scientific synthesis. *PLoS ONE* 9, e101298. <https://doi.org/10.1371/journal.pone.0101298>.
- Parvatker, A.G., Eckelman, M.J., 2019. Comparative evaluation of chemical life cycle inventory generation methods and implications for life cycle assessment results. *ACS Sustain. Chem. Eng.* 7, 350–367. <https://doi.org/10.1021/acssuschemeng.8b03656>.
- Pavón, S., Heubner, C., Michaelis, A., 2026. Safeguarding raw material basis in Europe through electrochemical integration in hydrometallurgical processing. *Resour. Conserv. Recycl.* 231, 108937. <https://doi.org/10.1016/j.resconrec.2026.108937>.
- Pavón, S., Kahl, M., Hippmann, S., Bertau, M., 2022. Lithium recovery from production waste by thermal pre-treatment. *Sustain. Chem. Pharm.* 28, 100725. <https://doi.org/10.1016/j.scp.2022.100725>.
- Pavón, S., Kaiser, D., Bertau, M., 2021a. Recovery of Al, Co, Cu, Fe, Mn, and Ni from spent LIBs after Li selective separation by COOL-process – Part 2: solvent extraction from sulphate leaching solution. *Chem. Ing. Tech.* 93, 1840–1850. <https://doi.org/10.1002/cite.202100101>.
- Pavón, S., Kaiser, D., Mende, R., Bertau, M., 2021b. The COOL-process—a selective approach for recycling lithium batteries. *Metals* 11, 259. <https://doi.org/10.3390/met11020259>.
- Petrakis, E., Alexopoulos, I., Pantelaki, O., Karmali, V., Komnitsas, K., 2025. Advances in mineral processing of hard-rock lithium ores: a comprehensive review. *Min. Metall. Explor.* <https://doi.org/10.1007/s42461-025-01227-y>.
- Piccinno, F., Hischier, R., Seeger, S., Som, C., 2016. From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies. *J. Clean. Prod.* 135, 1085–1097. <https://doi.org/10.1016/j.jclepro.2016.06.164>.
- Rivero-Falcón, A., López-López, Y., Peñate Suárez, B., Melián-Martel, N., 2025. Performance evaluation of nanofiltration membranes for SWRO brine valorisation: insights from a pilot plant under real conditions. *Sep. Purif. Technol.* 359, 130774. <https://doi.org/10.1016/j.seppur.2024.130774>.
- Sacchi, R., Terlouw, T., Siala, K., Dirnhaichner, A., Bauer, C., Cox, B., Mutel, C., Daioğlu, V., Luderer, G., 2022. PROspective environmental impact asSEment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renew. Sustain. Energy Rev.* 160, 112311. <https://doi.org/10.1016/j.rser.2022.112311>.
- Santero, N., Hendry, J., 2016. Harmonization of LCA methodologies for the metal and mining industry. *Int. J. Life Cycle Assess.* 21, 1543–1553. <https://doi.org/10.1007/s11367-015-1022-4>.
- Stamp, A., Lang, D.J., Wäger, P.A., 2012. Environmental impacts of a transition toward e-mobility: the present and future role of lithium carbonate production. *J. Clean. Prod.* 23, 104–112. <https://doi.org/10.1016/j.jclepro.2011.10.026>.
- Steubing, B., De Koning, D., Haas, A., Mutel, C.L., 2020. The Activity Browser — an open source LCA software building on top of the brightway framework. *Softw. Impacts* 3, 100012. <https://doi.org/10.1016/j.simpa.2019.100012>.
- SUEZ, 2025. Conventional recessed plate filter press. In: <https://www.suezwaterhandbook.com/processes-and-technologies/liquid-sludge-treatment/filter-press/conventional-recessed-plate-filter-press> accessed 9.24.25.
- Sun, X., Wang, F., Wang, P., Zhao, D., Zhao, M., Jiao, X., Li, J., Li, Z., Geng, Y., Sun, L., 2025. Risk analysis and eco-design strategies for critical mineral resources in China's vehicle electrification process. *Resour. Conserv. Recycl.* 216, 108156. <https://doi.org/10.1016/j.resconrec.2025.108156>.
- Swain, B., 2017. Recovery and recycling of lithium: a review. *Sep. Purif. Technol.* 172, 388–403. <https://doi.org/10.1016/j.seppur.2016.08.031>.
- Światowska, J., Barboux, P., 2015. Chapter 4 - lithium battery technologies: from the electrodes to the batteries. In: Chagnes, A., Światowska, J. (Eds.), *Lithium Process Chemistry*. Elsevier, Amsterdam, pp. 125–166. <https://doi.org/10.1016/B978-0-12-801417-2.00004-9>.
- Thonemann, N., Schulte, A., Maga, D., 2020. How to conduct prospective life cycle assessment for emerging technologies? A System. *Rev. Methodol. Guid. Sustain.* 12, 1192. <https://doi.org/10.3390/su12031192>.
- Tsoy, N., Steubing, B., Van Der Giesen, C., Guinée, J., 2020. Upscaling methods used in ex ante life cycle assessment of emerging technologies: a review. *Int. J. Life Cycle Assess.* 25, 1680–1692. <https://doi.org/10.1007/s11367-020-01796-8>.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21, 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>.
- Wills, B.A., Finch, J.A., 2016. Comminution. *Wills' Mineral Processing Technology*. Elsevier, pp. 109–122. <https://doi.org/10.1016/B978-0-08-097053-0.00005-4>.