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Lithium in Latin America: A dynamic material flow analysis and mapping CO_2, water, and land footprints to 2050

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ABSTRACT

The rapid expansion of electrification is driving soaring lithium demand, raising concerns about supply sustainability and ecological impacts. This study traces lithium flows across the Lithium Triangle and 27 other Latin American and Caribbean (LAC) countries, projecting sustainability through 2050 under alternative technology scenarios. Results show a major imbalance: in 2022, lithium exports (as lithium carbonate equivalent, LCE) exceeded imports (products containing lithium, converted to LCE) by over 100-fold, and will remain 10 times higher by mid-century. Technology-driven approach could mitigate impacts, avoiding up to 29 Mt of CO_2 emissions, conserving 1384 Mm^3 of water, and restoring 1973 km^2 of land. Despite vast reserves, LAC holds only a marginal position in the global value chain. Moving from resource supplier to integrated actor will require sustainable mining, investment in local manufacturing, and expansion of recycling to secure economic gains alongside environmental resilience.

1. Introduction

The global transition to decarbonization and electrification is driving extraordinary demand for lithium—a critical component in lithium-ion batteries (LIBs) (Xu et al., 2020, Graham et al., 2021). Due to its high energy density, long lifespan, and superior electrochemical properties, lithium remains the dominant charge carrier in LIBs. While alternative batteries are being explored, they often fall short in performance, making it unlikely to be replaced in the near future (IEA, 2022, Tabelin et al., 2021). Over the past decade, global lithium production has more than tripled and is projected to exceed 2.2 Mt of lithium carbonate equivalent (LCE) by 2050 (IEA 2021, Hund et al., 2023). This surge in consumption has started raising doubts about the long-term sustainability and resilience of lithium supply chains.

Previous studies on lithium flows and stocks have primarily examined supply-demand dynamics in major resource-importing regions such as the U.S, the EU and China (Kavanagh et al., 2018, Sun et al., 2018), often emphasizing resource availability, criticality and the role of electric vehicles (EVs) (Ballinger et al., 2019, Sun et al., 2024) in driving demand and future waste generation (Sun et al., 2018, Ballinger et al., 2019, Sun et al., 2024, Simon et al., 2015, Petavratzi and Josso, 2021, Song et al., 2019, Ziemann et al., 2012, Miatto et al., 2021, Chang et al., 2009, Sun et al., 2017, Fujita et al., 2021, Guyonnet et al., 2015, Kamran et al., 2021). However, relatively limited attention has been given to the environmental burdens, trade asymmetries, and recycling challenges faced by producer regions (Graham et al., 2021, Duarte Castro et al., 2021, Harppecht et al., 2021). Additionally, many are restricted to short-term assessments and neglect long-term recycling integration (Maisel et al., 2023, Matos et al., 2022, Shafique et al., 2022, Hao et al., 2017, Lu et al., 2017, Liu et al., 2021). A comprehensive overview of previous research is provided in Supplementary Information SI-1 and Table S1 (Graham et al., 2021, Duarte Castro et al., 2021, Harppecht et al., 2021, Maisel et al., 2023, Baars et al., 2021, Jin et al., 2022, Richa et al., 2014).

Latin America plays a critical role in global lithium supply with the Lithium Triangle (Chile, Argentina, and Bolivia), which holds over half of the world's lithium resources (USGS 2024, CEPAL 2023). In the region, brine-based lithium extraction is the main source of lithium, which

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emits significantly less CO_2 than hard-rock mining, making it a likely preference in future supply scenarios (Tabelin et al., 2021, Proenza et al., 2020, Kelly et al., 2021, Schenker et al., 2022). The extraction comprises drilling into aquifers followed by slow solar evaporation process (Tabelin et al., 2021, Blair and Balcázar Morales, 2022). The challenges associated include water usage, land occupation, and waste generation, threatening ecosystems and local communities (Schenker et al., 2022, Vera et al., 2023, Flexer et al., 2018, Owen et al., 2023). Additionally, the region's susceptibility to natural disasters such as earthquakes and droughts, combined with political and economic instability, aggravates the risk of resource supply (Sun et al., 2018, Ballinger et al., 2019). Globally, the COVID-19 pandemic and ongoing geopolitical tensions further underscore the urgent need for a reliable and sustainable lithium supply (Tabelin et al., 2021, IEA 2023).

Despite its resource wealth, Latin America remains largely peripheral in the battery value chain, exporting raw materials while importing high-value technologies. Furthermore, the potential to recover lithium from end-of-life (EOL) batteries within Latin America remains underexplored, despite growing domestic markets and rising waste volumes.

This study addresses these gaps by quantifying lithium stock and flow patterns across 30 LAC countries, including Brazil, Mexico, Argentina, Bolivia, Chile, Colombia, and Ecuador (Table S2). Brazil's spodumene-based hard rock mining was considered to reflect the region's evolving lithium production landscape. Combining material flow analysis (MFA) (Müller et al., 2014), scenario modelling, and prospective environmental footprint assessment based on life-cycle analysis (LCA) (Kelly et al., 2021, Schenker and Pfister, 2025, Lagos et al., 2024) we evaluated the extent to which the region can address supply-side challenges, mitigate extraction risks, and manage environmental impacts (including CO_2 emission, water use, and land occupation). Particular attention is given to opportunities for increasing recycling rates through recovery of lithium from discarded LIBs, thereby reducing dependence on primary extraction.

2. Materials and methods

2.1. System definition and framework

This study integrates an anthropogenic metabolism analysis, a dynamic MFA, and a prospective environmental footprint assessment to examine lithium across 30 LAC countries. Lists of target countries and abbreviations are available in Table S2 and Table S3, respectively. Lithium exists in various chemical forms throughout production and use, but industry statistics are typically reported in LCE. Therefore, we used LCE as the standard accounting unit, which allows a convenient comparison with other studies. We tracked and quantified lithium flows and stocks from 2000 to 2022, and subsequently projected future production and associated environmental impacts—including CO_2 emissions, water use, and land occupation—as well as use and recycling potential through to 2050. Further information in SI-2.1.

2.2. Estimation of current and future lithium extraction and demand

The assessment began with lithium extraction estimation from brines, including chemical processes, recirculation, and lithium concentrate (spodumene) mining and processing in Brazil. While Mexico and Peru also hold lithium resources, their contribution remains minor. Peru, for instance, holds only about 1 % of identified resources, and its extractive sector remains focused on copper (its main export) and gold, making near-term lithium production unlikely (CEPAL 2023, ECLAC, 2024, Fornillo and Lampis, 2023).

To explore potential outcomes for lithium extraction, we modeled three different trajectories (in different lithium demand speeds):

- Low: considers only currently operating projects in Chile, Argentina, and Brazil, while Bolivia contributes marginally.
- High: assumes full production capacity of both operational and committed projects in all four countries.
- Middle: reflects moderate optimistic growth, positioned between the two extremes.

Additional information, data sources, and pathway assumptions are detailed in SI-2.2 and Table S4–S5 and Fig. S1.

An anthropogenic metabolism analysis was considered to assess and forecast future lithium demand in the region. Historically, lithium was primarily used in ceramics and glass, lightweight metal alloys, and consumer electronics. However, lithium demand patterns are now increasingly shaped by the electrification of transport, especially the shift toward EVs and electric buses (Sun et al., 2018, Hao et al., 2017). LAC countries are expected to follow global trends, transitioning from hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) to full battery electric vehicles (BEVs), as illustrated in Fig. S2. To align demand-side projections with supply pathways in the LAC case, we developed three adoption narratives based on varying levels of EV penetration:

- Fossil Fuel Dominance (FFD) (low pathway): fossil fuel-powered vehicles continue to dominate the landscape. With marginal incentives for EVs, their market stays below 5 % by 2050 (CEPAL 2023). As of 2022, average penetration rates across the region were below 1 %, with Brazil leading the regional market, followed by Mexico (CEPAL 2023). Even assuming an annual growth rate of 10 %, EV adoption would only reach around 5 % by 2050. This pathway emphasizes the current lack of significant EV deployment in the LAC region.
- Green Drive (GD) (middle pathway): an active shift towards EVs occurs. LAC adopts mid-level incentives according to their economic capacities. EV sales range from 1 % to 25 %.
- Total City EV (TCEV) (high pathway): envisioning rapid EV adoption, assuming EVs are mainly imported and substantial government incentives drive EV penetration, with major cities or capitals achieving 100 % new EV sales (Table S6),

In our analysis, the evolution of EV battery chemistry followed current global trends, with a potential transition from NMC 622 to 811 or 111 alongside an increasing use of LFP batteries, influenced by China's battery trends, especially in electric buses and EVs (SI-2.2 and Table S7–S8) (Xu et al., 2020, Petavratzi and Josso, 2021). For non-battery functional uses and battery uses, excluding EVs, the forward projection was based on the assumption of growing per capita ownership and unit of gross domestic product (GDP) assumptions for each country in the region (ITU Hub 2024). Note that the future pathway is highly uncertain and can be affected by many influencing factors, such as economic capacities, policy incentives, and technological trends of the assessed countries (Duarte Castro et al., 2021, Jones et al., 2023). Recycling and waste management were also key considerations. From 2000 to 2022, the LAC region faces an ineffective recycling system of waste electrical and electronic equipment (WEEE) and batteries, with an average collection rate of <3 % (Wagner et al., 2022, Jones et al., 2021). In this study, in the context of EOL and waste management, only LIBs were assumed to be collected and recycled using existing technology, while the rest are typically disposed of in landfills. Current battery recycling processes prioritize nickel or cobalt recovery, limiting lithium availability for secondary uses (Jin et al., 2022, Ambrose and Kendall, 2020, Ciez and Whitacre, 2019, Wang et al., 2023). Although the global lithium recycling yield is <1 %, this is expected to improve with increased LIB adoption and advancements in recovery and reprocessing technologies (Lee et al., 2022, Santos et al., 2021).

2.3. Dynamic material flow analysis

To quantify how lithium moves through the LAC region, a dynamic

MFA was conducted from 2000 to 2050. The study considers nine key processes: brine deposits, ore deposits, tailings storage, ore mining, brine chemical production, overseas manufacturing, in-use stock, waste management and recycling, and landfill. The analysis covers focus on lithium producers—Chile, Argentina, Brazil, and Bolivia as they are the source of all primary lithium flows. At the same time, demand from all 30 LAC countries, including these four countries already mentioned, plays an important role as net importers and users of lithium-containing products such as EVs and consumer electronics. These products accumulate in societal stocks and eventually become secondary lithium resources. The demand from these 30 countries actively influences the volume of lithium-containing goods imported into the region and the potential for future circularity. Non-producing countries are not passive; they are the locations where end-of-life batteries will be collected.

Material flows and stocks are examined with a focus on presenting the current situation in 2022 and the final year, 2050, alongside an assessment of cumulative totals of flows and stocks over the entire analysis period, highlighting both primary extraction in producing nations and the role of 30 countries in driving regional demand, stock accumulation, and secondary resource availability.

Historical extraction data were obtained from company reports and government statistics (USGS 2023, International Trade Centre 2024) for Chile, Argentina, and Brazil. Additionally, mass losses, particularly lithium losses into tailings streams, were quantified (Kelly et al., 2021, Delboni et al., 2023). Historical import and export data were obtained from the UN Comtrade Database (UN Comtrade 2023) and Trade Map (International Trade Centre 2024) to identify lithium products and applications in the region. Eight key end-use goods were categorized using trade tariff codes (Table S9). Manufacturing of lithium-containing products used in the region was assessed with a product-level approach as outlined by Müller et al. (Müller et al., 2014, Brunner and Rechberger, 2016) and Harper et al. (Harper, 2008).

Regional EV deployment was evaluated via vehicle association statistics (SI-2.3 and Table S10–S11). Net addition to stock was calculated as the difference between inflows and outflows, employing a top-down approach (Müller et al., 2014, Werner et al., 2018, Gómez et al., 2023). In this study, inflows were calculated based on historical sales data, whereas outflows are modeled through probabilistic lifetime functions for each commodity to estimate their lifespan before recycling or disposal. This study employs average commodity lifespans obtained from the literature (Table S12) (Ballinger et al., 2019, Richa et al., 2014, Zeng et al., 2022, Rith et al., 2020). Lithium content for products was calculated as LCE using conversion coefficients and data on lithium percentages in various commodities. For LIBs, the LCE estimation considered changes over time in lithium content and variations in goods' size and weight. Content estimates relied on arithmetic averages, with upper and lower bounds indicating standard deviation uncertainty. These assumptions, detailed in Fig. S3, were based on a comprehensive literature review (Xu et al., 2020, Jones et al., December 21, 2023, Zeng et al., 2022, Wagner-Wenz et al., 2023).

At the waste management and recycling stage, we explored technological options to recover LCE or cathodes as secondary resources by 2050, highlighting varying impacts on waste management across pathways. While the FFD pathway results in limited lithium recycling due to modest EV deployment, greater EV adoption in pathways like GD and TCEV compels the region to implement collection programs, local pretreatment processes, and recycling technologies until 2050. Some recycling technologies for LIB recovery include pyrometallurgy, hydrometallurgy (Fujita et al., 2021, Šimaitis et al., 2023), and direct recycling (Jin et al., 2022, Wagner-Wenz et al., 2023) (SI-2.3). Our analysis combines two recycling technologies pyrometallurgy and hydrometallurgy, and additionally considers direct recycling, assuming improvements over time in recovery efficiency, collection rates, and pretreatment yields (Figs. S4–S5) (Fujita et al., 2021, Santos et al., 2021, Wagner-Wenz et al., 2023, Šimaitis et al., 2023).

This framework enables a detailed understanding of lithium accumulation in LAC society, EOL flows, and the potential for future recycling. Outputs from this MFA underpin the scenario analysis described earlier, offering insight into the interplay between extraction, consumption, and circularity in LAC's evolving lithium economy.

2.4. Environmental footprint assessment and scenario analysis

This study evaluated lithium production's environmental footprints, focusing on CO_2 emissions, water use, and land occupation changes (Schenker et al., 2022, Vera et al., 2023, Flexer et al., 2018, Mousavinezhad et al., 2024). These categories were selected because they represent the most critical and consistently reported environmental pressures associated with lithium extraction in the region.

The footprint assessment relied on life-cycle assessment (LCA) factors directly referred from literature review and then projected to 2050 to ensure a comprehensive evaluation (Kelly et al., 2021, Lagos et al., 2024, Mousavinezhad et al., 2024). The underlying life cycle applied a

Table 1
Environmental impact factors.

Factor	Country	Technology-Frozen Scenario (TFS) **2022–2050**	Technology-Enhanced Scenario (TES) **2022–2050**
GHG emission $kgCO_2eq/kg$ Li_2CO_3	Chile (Schenker et al., 2022, Grant et al., 2020, Mas-Fons et al., 2024)	4.02	4.02 to 2.01
	Argentina (Schenker et al., 2022, Grant et al., 2020, Mas-Fons et al., 2024)	7.73	4.022 to 3.87
	Brazil (Kelly et al., 2021, Schenker et al., 2022, Lagos et al., 2024)	20.40	20.40 to 15.69
	Bolivia (Schenker et al., 2022, Lagos et al., 2024)	7.39	7.39 to 3.69
Water use (water in brine + fresh water) (t water use / t of Li_2CO_3)	Chile (Schenker et al., 2022, Vera et al., 2023, Flexer et al., 2018, Mousavinezhad et al., 2024)	363.50	363.50 to 217.18
	Argentina (Vera et al., 2023, Flexer et al., 2018, Mousavinezhad et al., 2024, Halkes et al., 2024)	520.00	520.00 to 295.5
	Brazil (Schenker et al., 2022, Vera et al., 2023, Mousavinezhad et al., 2024, Halkes et al., 2024)	62 (t fresh water/ t of Li2CO3)	62 to 31 (t fresh water/ t of Li2CO3)
	Bolivia (Vera et al., 2023, Flexer et al., 2018, Mousavinezhad et al., 2024, Halkes et al., 2024)	441.68	441.68 to 256.34
Land occupation (m^2/ t of Li_2CO_3)	Chile (Schenker et al., 2022, Vera et al., 2023, Mousavinezhad et al., 2024, Halkes et al., 2024)	3656	3656 to 866
	Argentina (Vera et al., 2023, Flexer et al., 2018, Mousavinezhad et al., 2024, Halkes et al., 2024)	2949	2949 to 1109
	Brazil (Schenker et al., 2022, Vera et al., 2023, Mousavinezhad et al., 2024, Halkes et al., 2024)	335	335 to 168
	Bolivia (Schenker et al., 2022, Vera et al., 2023, Mousavinezhad et al., 2024, Halkes et al., 2024)	2949	2949 to 1474.50

Note: The values present in this table represent country level averages across all brine pools from LCA studies, based on a cradle-to-grave assessment of LCE production, with Bolivia's data specifically assessed for the period from 2025 to 2050. Additional information is in SI-2.4, Supporting Data Fig. 4, and Figs. S17-S20.

cradle-to-gate system boundary, covering lithium extraction (brine and ore) through processing into LCE (Table 1). This study uses the findings from LCA studies as factors to assess environmental impacts. Downstream stages, including manufacturing, product use, and end-of-life management, were excluded, as the analysis emphasizes the extraction and processing phases most relevant to LAC's role as a resource supplier. While other categories—such as freshwater ecotoxicity—are also relevant, particularly in relation to chemical processing (Chordia et al., 2022), robust and consistent regional data remain limited. Therefore, this study focused on CO_2, water, and land use as the most data-supported and regionally significant categories.

Two scenarios were analyzed to explore potential outcomes: the technology-frozen scenario (TFS), which assumes no technological innovation, with mining and processing practices remaining as they are today—resulting in unchanged environmental impact factors through 2050; and the technology-enhanced scenario (TES), which assumes the adoption of sustainable mining practices, including technological innovations, responsible practices and circular economy principles (Flexer et al., 2018, Alessia et al., 2021), described in more detail below. This approach aims to improve efficiency and reduce environmental impacts across these processes, potentially lowering these impacts by nearly 50 % by 2050 (Schenker and Pfister, 2025, Istrate et al., 2024). All environmental impact factors are detailed in Table 1.

For the carbon emissions, the analysis used emission factors associated with producing one ton of LCE from brine extraction and spodumene. The TFS assumes emissions remain constant with current technologies, while the TES incorporates renewable energy sources such as photovoltaic panels—leveraging the region's high solar potential—as well as Carbon Capture and Utilization (CCU) technologies in the mining and production stages as key decarbonization strategies to reduce emissions (Schenker et al., 2022, Lagos et al., 2024, Mousavinezhad et al., 2024, Istrate et al., 2024, Kanwal et al., 2025).

Water use was analyzed by distinguishing between brine water evaporation and freshwater consumption in chemical processes, using specific values tailored to regional brine extraction projects. In the TFS, significant water use is associated with brine evaporation pools. The TES incorporates direct lithium extraction (DLE) technology, which requires chemical sorbents, ion-exchange membranes, or solvents to recover lithium. This approach reduces the number of evaporation pools needed but increases freshwater demand, which for this pathway is treated and recirculated. By adopting DLE, the lifespan of brine sources can be extended, improving sustainability and preserving lithium resources (Vera et al., 2023, Flexer et al., 2018, Mousavinezhad et al., 2024, Halkes et al., 2024).

Land occupation was calculated based on the area directly affected by extraction methods. For brine extraction under the TFS, this requires large evaporation pools, driving significant land use. The land occupation factors used for the assessment were derived from Mousavinezhad et al. (2024) (Mousavinezhad et al., 2024). In this study, the area for brine operations includes evaporation ponds, processing plants, wellfield areas, and disposal areas. In Brazil's case, for hard rock spodumene, land occupation was estimated based on Australian operations as a proxy. Under the TES, DLE reduces land requirements by minimizing the need for pools, further decreasing land disturbance, and incorporating restoring sites after lithium extraction. The reduced land footprint of brine operations with DLE was also based on the study from Mousavinezhad et al., accounting for processing plant and wellfield areas with smaller pool areas.

For Brazil's spodumene-based lithium extraction, environmental impact factors such as CO_2 emissions, water usage, and land occupation were estimated using Australian hard rock mining factors as a reference.

2.5. Sensitivity and uncertainty analysis

A sensitivity analysis was conducted to identify the most influential parameters in the model. The EOL LCE recovery potential, and CO_2 emissions flows were selected as primary indicators. The parameters evaluated included: production yields from lithium sources in LAC, collection and pretreatment rates of EOL products, recovery efficiencies of the applied methodologies (pyrometallurgy + hydrometallurgy and direct recovery), and CO_2 emission factors from different lithium sources. Each parameter changed individually by ±10 %, and the resulting change in the indicator was compared to its default value. The confidence and potential variability of these parameters were also assessed with respect to their sources, representativeness, and recent trends (Table S13).

The sensitivity S of each parameter x was calculated as shown in:

$$S(x \pm 10\%) = \frac{E(x \pm 10\%)}{E(x)}$$

Where x represents the analyzed parameter; E(x) is the total cumulative value of the indicator under the default parameter, and $E(x \pm 10\ \%)$ is the total cumulative value calculated with $a \pm 10$ % variation in x. $S(x \pm 10\ \%)$ quantifies the sensitivity of the indicator to a 10 % increase or decrease in parameter x.

3. Results and discussion

3.1. Lithium production and demand in the LAC by 2050

To meet global carbon neutrality targets alongside rising EV adoption, lithium production is projected to triple by 2050, reaching 2.2 Mt LCE (Hund et al., 2023, Alessia et al., 2021, Thurtell et al., 2023). Following a conservative (middle) pathway throughout this study, as shown in Fig. 1, it is estimated that Latin America will account for 40 % of global annual lithium production by 2050, totaling 883 metric kilotons (kt) of LCE. This estimation includes new lithium projects in Argentina, Brazil, and Bolivia, along with production expansions in Chile and Brazil (CEPAL 2023, Jones et al., December 21, 2023). Chile is projected to dominate brine production (65 %), followed by Argentina (26 %) and Bolivia (9 %), with total brine production of 810 kt, and Brazil's lithium spodumene production reaching 73 kt.

The Lithium Triangle holds an estimated 300 Mt of LCE (USGS 2023), potentially enough to meet global demand for over a century (Proenza et al., 2020, USGS 2023). However, the challenges faced by the lithium industry go beyond resource depletion. Ensuring a reliable supply while minimizing environmental impact is crucial for long-term lithium sustainability (Baars et al., 2021). Our analysis underscores the urgent need for effective resource management, investment in refining

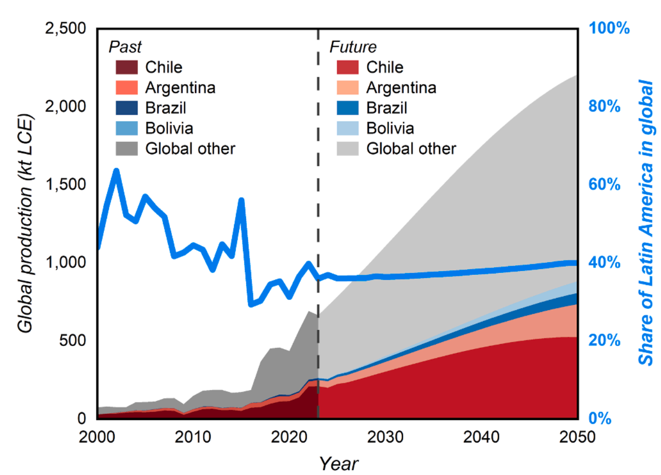

Fig. 1. Lithium global demand and Latin America production 2000–2050 middle pathway. Latin America's contribution to the global lithium supply from 2000 to 2022 is assessed, and to forecast from 2023 to 2050, the middle production pathway—falling between the low and high production forecast—is used. Detailed pathways (low-high) are available in Figs. S6–S7.

infrastructure, and the adoption of sustainable practices to entirely capitalize on the region's lithium potential (Vera et al., 2023, Flexer et al., 2018).

In response, Chile, the leading producer, aims to implement the DLE technologies (Vera et al., 2023, Mousavinezhad et al., 2024) to mitigate brine evaporation and comply with stricter environmental standards (Gómez, 2023, Gob.cl 2024, CORFO 2024). Argentina's vast untapped resources position it for a growing role (Devincenzi, 2024). Bolivia plans to launch production from the Uyuni salt flats by 2025, targeting 50 kt annually (Blair and Balcázar Morales, 2022, Jones et al., December 21, 2023, Jamasmie, 2024). Brazil, with its mineral resources, is expected to emerge as a key regional supplier. Overall, Latin America's lithium production landscape is likely to evolve from a Chile-dominated model to a more diversified, four-country framework (Delboni et al., 2023, Maxwell and Mora, 2020), strengthening the region's strategic role in global energy transitions. Therefore, this diversification might represent an opportunity to improve the region's collective bargain power. However, realizing this potential depends on moving beyond fragmented competition and embrace cooperation. For example, Chile and Argentina with well-established lithium extraction could invest in refining capacity for raw materials from Bolivia and Brazil and create an integrated regional value chain (Orquera et al., 2025). Otherwise, competition for investment may replicate the structural dependencies that have long characterized resource sectors in the region.

Fig. 2 illustrates historical lithium import data (2000–2022) alongside three future pathways through 2050, highlighting past trends and projected regional demand. Latin America currently lacks a battery manufacturing industry, relying heavily on imports of lithium products (Fornillo and Lampis, 2023, Sanchez-Lopez, 2023). From 2000 to 2022, nearly 16 kt of LCE—<1000 t annually—were imported in finished goods, predominantly electronic devices containing LIBs (Hao et al., 2017, Miatto et al., 2020). Lithium in-use stock reached 9.4 kt over the past 22 years, with EVs accounting for 49 % and EOL and recycling flows remaining minimal. Despite the increase in EV registration since 2016,

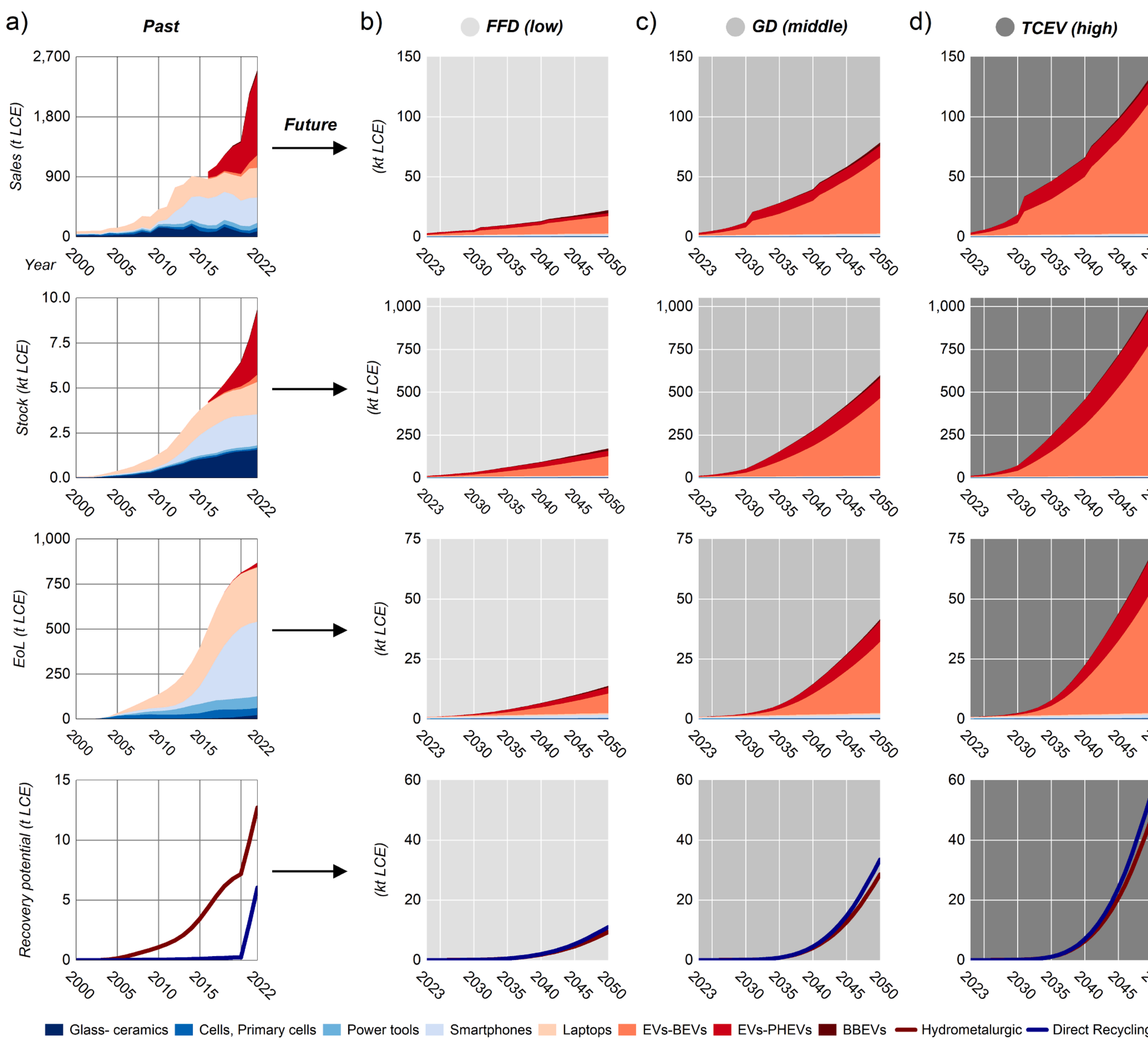

Fig. 2. Lithium historical data and future pathways in LAC region. This figure shows an assessment of imports, stocks, EOL lithium products, and recycling potential of lithium-containing products: a) shows historical data from 2000 to 2022. Forecasted estimations to 2050 are presented in b) FFD (low EV penetration), c) GD (middle EV penetration), and d) TCEV (high EV penetration). In the figure, BBEVs refer to electric buses. Historical data are expressed in tons of LCE, while future estimations are presented in metric kilotons (kt) of LCE.

the region still accounts for only 7 % of global new sales (S Kohli et al., 2024). Likely, due to common constraints and barriers that Latin American countries and their emerging economies face in EV deployment (CEPAL 2023, Jones et al., December 21, 2023, Sanchez-Lopez, 2023, Ruoso and Ribeiro, 2022, Vallarta-Serrano et al., 2022, Lopez-Arboleda et al., 2023, Vera et al., 2017, Aymeric and François, 2017).

By 2050, our study projects that EVs will require 19 kt of LCE under the FFD pathway and 132 kt under the TCEV pathway. Lithium in-use stock from LIBSs will range from 172 to 1024 kt, depending on the scenario parameters, creating a significant secondary resource pool available for post-2050 recovery. While these secondary resources present opportunities, they also pose challenges. Currently, e-waste collection rates in LAC remain below 3 % (Wagner et al., 2022, Alvarenga and Perrier, 2018), with valuable components shipped to Europe, China, and the USA for recovery (Alvarenga and Perrier, 2018). Recycling initiatives are vital for reducing the need for virgin materials in battery production (Further details SI-3.1).

In 2050, EVs will dominate the EOL stage across scenarios. Under the FFD pathway, secondary lithium resources are expected to be concentrated in Brazil, Mexico, and Colombia, reflecting the current distribution (14 kt). Conversely, the GD and TCEV pathways show a more balanced regional distribution, with EOL products reaching 42 kt and 69 kt, respectively. It is important to note that this study focuses on domestically used batteries in the LAC region. While incorporating import and export data on spent batteries would be beneficial, no reliable information is currently available.

3.2. Flows and stocks of lithium in LAC to 2050

Fig. 3 illustrates estimated lithium flows to 2050 at the regional level, considering historical data and forecast assessments (middle) pathway. The dynamics of lithium flows and stocks for 2022 and 2050, as well as the cumulative period from 2023 to 2050, are analyzed, while alternative pathways (low and high) are detailed in Figs. S6–S16. Over the past decade, global lithium demand has surged, driving a significant increase in Latin American production. Since 2000, regional demand has grown about 42-fold. By 2022, the in-use stock is 1.7 kt.

Between 2023 and 2050, Latin America's primary lithium extraction is projected to total around 20 Mt, with brine and ore mining contributing 94 % and 6 % (Fig. 3c). Brine production involves evaporation, purification, and carbonation, yielding 15 Mt of export products and 4.1 Mt of by-products. These by-products can be reinjected in the deposit,

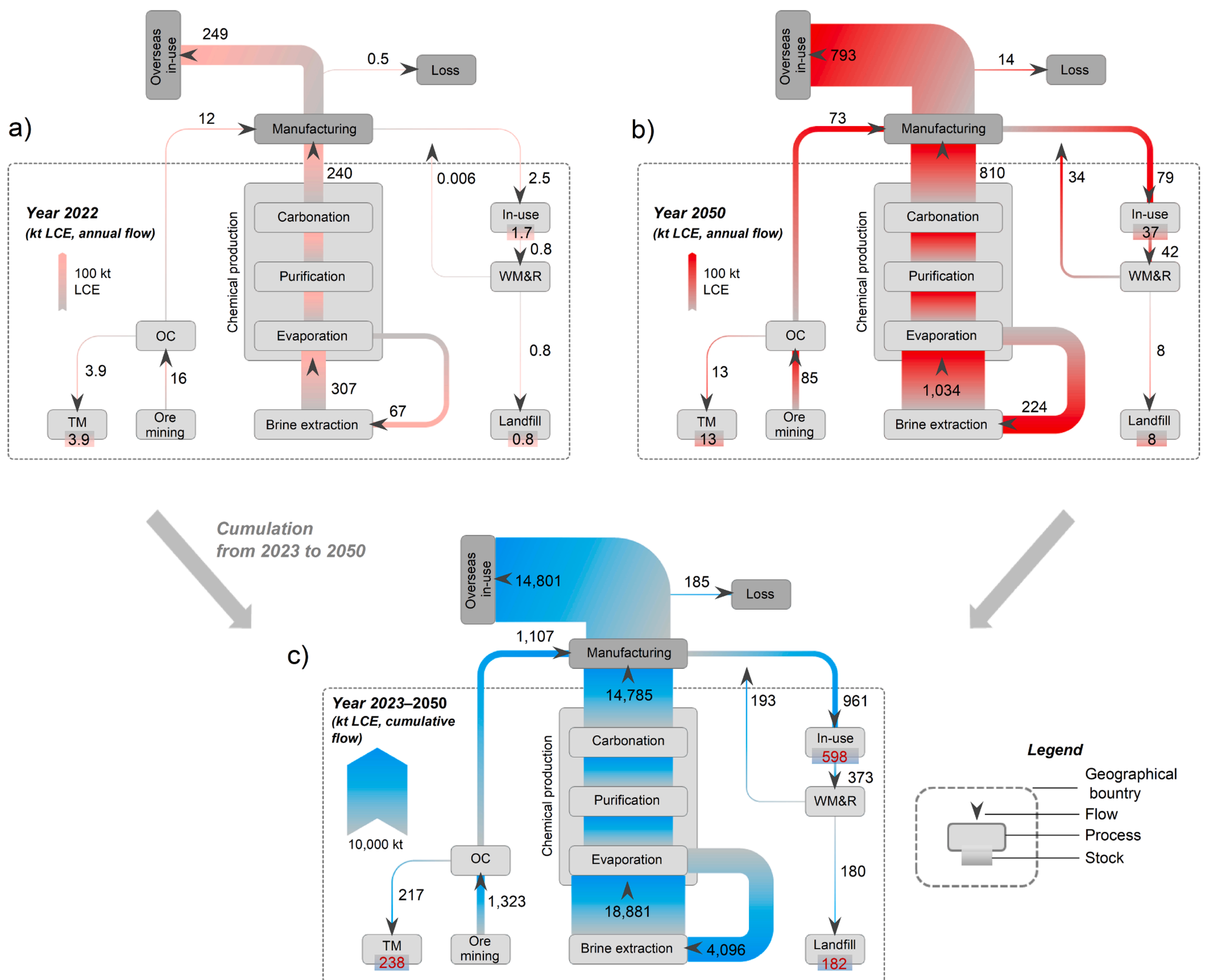

Fig. 3. MFA in LAC years 2022 and 2050, and cumulative 2023–2050. a) and b) show flows for single years (2022 and 2050, respectively), while c) shows cumulative flows for the 27-year period starting from 2023 and a cumulative stock since 2000. Values in red indicate the stock in tailings and the in-use stock of products (total amount). TM: Tailings management, OC: Lithium ore concentration, WM&R: Waste management and recycling.

potentially affecting its concentration (Kelly et al., 2021, Maxwell and Mora, 2020, Cabello, 2021, Bustos-Gallardo et al., 2021). Ore mining generates 1.1 Mt of export products and 238 kt of waste over fifty years. This waste requires additional facilities for processing and stacking, posing engineering and environmental risks, such as the collapse of tailings piles and land occupation (Kelly et al., 2021, Meng et al., 2021, Abdullah et al., 2019). These outcomes might lead to tensions with the agricultural sector and local communities over water sources, land use, and contamination risks. While this study does not explicitly model social acceptance and community impacts, these factors are critical and could significantly influence the pace and scale of future lithium exports. Future research work could benefit from integrating these dimensions into a prospective assessment of lithium supply chains. Ultimately, sustainable production requires to focus on efficient water use, minimizing land disturbance, secure tailings handling, and active community engagement.

Direct imports are estimated at 961 kt, with EOL products at 373 kt, and a cumulative stock of 589 kt. Effective collection and recycling might recover 167 kt from hydrometallurgy and 193 kt from direct recycling, covering about 20 % of cumulative demand and reducing potential landfill waste by 52 %. By 2050, EOL products will constitute 54 % of imported lithium and the in-use stock will account for 598 kt, highlighting the need for effective recovery and recycling processes of secondary sources in LAC (Petavratzi and Josso, 2021, Sun et al., 2017, Zheng et al., 2022, S IEA 2024).

Our sensitivity analysis indicates that the largest source of uncertainty in the model arises from the recycling rates for pyrometallurgy-hydrometallurgy and direct recycling. Within this, uncertainties in collection rates and recovery efficiencies have a substantial influence on model outcomes. In the case of direct recycling, the main source of variability is the pretreatment process required to separate cathodes. The second most influential factor is regional EV deployment targets, which, although based on government projections, remain highly uncertain. In contrast, uncertainties related to other lithium-ion batteries, such as those from small electronic devices, are relatively minor. These findings highlight the importance of carefully monitoring recycling performance, collection rates, and EV deployment, as these factors exert the greatest influence on the robustness of projected lithium flows in the MFA (Table S13).

On a per capita in-use stock basis, our findings can be compared with those of other regions. Miatto et al. and Miedema et al. estimated averages of 82 g and 44 g LCE in the USA and EU from 2000 to 2016 (Miatto et al., 2020, Miedema and Moll, 2013). In China, Liu et al. reported an average of 8.6 g LCE per person until 2017, rising to over 18 g LCE with rapid EV adoption post-2018 (Liu et al., 2021). Our research shows that in LAC, the lithium in-use stocks were 7.9 g LCE per person in 2017, increasing to 15 g LCE by 2022. These results highlight the differences between the major lithium consumers—the USA, EU, and China—and LAC (Liu et al., 2021, Miatto et al., 2020, Miedema and Moll, 2013, Usai et al., 2022), which are not just a reflection of EV adoption targets. These disparities reflect LAC's role as a supplier of raw materials for the consumption of wealthier nations and the region's socio-economic diversity, with factors like GDP and inequality influencing access to lithium-containing products, particularly EVs (Petavratzi and Josso, 2021, Sun et al., 2017, Zheng et al., 2022, S IEA 2024). While Chile and Argentina have achieved high economic levels, others face challenges such as poverty, inequality, and social disparities (Díaz et al., 2015, Acheampong et al., 2021). These discrepancies show that future lithium demand in LAC will remain uneven, resulting in disparities in regional stock accumulation. Further details are in SI-3.2.

Despite being home to over 60 % of global lithium resources) (USGS 2023), LAC remains largely marginal in the lithium value chain. Among the 30 LAC countries evaluated, only four—Argentina, Bolivia, Chile, and Brazil—produce lithium, with the rest serving as importers and consumers. In 2022, the region exported approximately 241 kt and imported just 2.5 kt of lithium products—an almost 100-fold disparity. By 2050, the imports are projected to represent 10 % of resource exports. This imbalance reflects the region's marginalization in the global lithium supply chain and a missed opportunity to capture greater economic value domestically. Most regional lithium production is used to meet global demand, with the USA, EU, and China as the primary markets (Sun et al., 2018, Sun et al., 2024, Shafique et al., 2022, Alessia et al., 2021). Limited local infrastructure for processing lithium, insufficient investment in battery manufacturing, and broader socio-economic and environmental challenges contribute to this marginalization.

Diversifying mining and processing locations can enhance supply chain resilience and foster economic growth in developing countries (IRENA 2023). While the Lithium Triangle maintains its strength in extraction, the region could capture higher-value activities and drive sustainable industrial development (Maxwell and Mora, 2020, Cabello, 2021). Currently, regional lithium demand is met through imports of lithium-containing products. Shifting part of overseas manufacturing to domestic production, the region might enhance its local lithium supply chain, address regional demand, and maintain a trade surplus. For example, Australia is advancing downstream processing to support domestic needs, while Indonesia has launched its first battery cell production facility and secured significant investments in batteries and EVs (Alessia et al., 2021, IRENA 2023, Government, 2023). In LAC, countries like Brazil and Mexico, with their established automotive manufacturing sectors, may play a significant role in developing manufacturing capabilities (Duarte Castro et al., 2021, Jones et al., 2021). Encouraging investments in processing and manufacturing within the region would unlock greater value from lithium resources. The Chinese EV giant BYD has expressed interest in establishing a LIB factory in the region, a move that could significantly bolster the supply chain and generate local employment. Japanese enterprises like Toyota and Panasonic continue to play a pivotal role in developing next-generation LIBs, such as the solid-state one, which may change the landscape of the global battery market (Tembo et al., 2024, Cui et al., 2024, Ottenheimer, 2023). LAC countries have the potential to foster mutually beneficial partnerships by exchanging their rich lithium resources for advanced technologies from Japan and China. Such collaborations could drive technological progress and creat mutually beneficial opportunities in the global lithium market (CEPAL 2023, Attwood, 2024, S Kohli et al., 2024).

From a resource efficiency perspective, many studies often emphasize waste management and recycling strategies as the primary approach for managing future lithium supply (Petavratzi and Josso, 2021, Lu et al., 2017, Richa et al., 2014, Christmann et al., 2015). While our study acknowledges the long-term importance of recycling, it offers a complementary short-term perspective: focusing on improving recovery rates in primary lithium extraction may be more efficient, given the relatively lower lithium volumes in EOL flows. This approach, although different, aligns with research on resource-rich, export-dependent nations (Werner et al., 2018, Zeng et al., 2022). For instance, lithium mining tailings in Brazil may contain recoverable amounts of lithium. In 2022, the region's EOL LIBs accounted for 0.8 kt, while mining waste was 3.9 kt, potentially accumulating to 21 kt since 2000. By increasing recovery rates in primary production (70 % to 85 %), mining waste is estimated to reach almost 238 kt by 2050—representing nearly 65 % of the region's cumulative EOL and secondary lithium resources. The findings show the importance of primary and secondary recovery strategies. This study is constrained by data limitations on spent battery trade and evolving battery chemistries, which could alter future projections. Future research should explore techno-economic assessments of battery recycling in LAC, the potential for sodium-based chemistries, and the integration of social and environmental justice considerations.

While improving recovery rates in primary lithium extraction is crucial in the short term, recycling will remain a cornerstone of long-term supply strategies. Recycling LIBs is an environmentally beneficial strategy that recovers valuable resources like nickel and cobalt, reduces landfill waste, and promotes sustainability (Baars et al., 2021, Wagner-Wenz et al., 2023, D'Adamo et al., 2020). While the EU's collaborative framework for recycling offers a strong example (Graham et al., 2021, Jin et al., 2022, Zhou et al., 2024), Japan stands out as a global pioneer. Policies like the Act on the Promotion of Effective Utilization of Resources and the Act on the Promotion of Recycling of Small Waste Electrical and Electronic Equipment have significantly advanced LIB collection and recycling in Japan (Cui et al., 2024, Morita et al., 2021). Environmental labels, designed to facilitate LIB classification, play a crucial role in improving collection, sorting, and recycling processes. Additionally, innovative technologies like direct cathode recycling have further boosted Japan's recycling efficiency (Tembo et al., 2024, Cui et al., 2024, Morita et al., 2021).

Globally, most large-scale recycling facilities are located near manufacturing plants, as scrap is expected to dominate feedstock in the coming decade, intensifying competition. China currently leads in recycling capacity and South Korea and Japan are emerging as significant players for recycling processes (Jin et al., 2022, Wagner-Wenz et al., 2023, Cui et al., 2024, Morita et al., 2021, S IEA 2024, Dai et al., 2024). In contrast, the secondary resource accumulation in LAC is underdeveloped and its recovery remains limited. The uneven geographic distribution of EOL LIBs implies that current waste flows are insufficient to support the development of cost-effective, large-scale recycling infrastructure. These challenges underscore the need for a coordinated regional strategy to gradually build recycling capacity. Nevertheless, the growing flow of EOL EV batteries by mid-century offers LAC countries the potential to build a substantial secondary resource pool (Zeng et al., 2022, Wagner-Wenz et al., 2023, Duda-Nyczak, 2024, Iqbal et al., 2023).

By adopting robust policies and fostering regional collaboration, LAC can draw valuable lessons from Japan and the EU's experience. Establishing secondary refining facilities in countries like Brazil could position LAC as a hub for lithium recovery, leveraging its strategic location and resource base (Fornillo and Lampis, 2023, Jones et al., December 21, 2023, Sanchez-Lopez, 2023). Mexico could also join these efforts or develop its own recovery industry to meet domestic and North American demand (Wagner-Wenz et al., 2023, Alessia et al., 2021). By integrating global best practices in recycling with extraction and refining with a circular economy framework for LIB recycling, LAC has the potential to diversify the supply chain and create opportunities for industrial upgrading. Such an approach would strengthen domestic consumption, enhance the regional market, and increase the region's participation in the global lithium value chain (Fornillo and Lampis, 2023, Jones et al., December 21, 2023, Sanchez-Lopez, 2023). This strategy highlights the importance of regional cooperation, investments and infrastructure development to procure region's lithium resource contributions to economic development and sustainable global energy transition.

Environmental responsibility and regulatory transparency must evolve alongside production. The global battery passport program stands out as an essential reference for fostering a responsible energy transition, through the incorporation of environmental indicators alongside considerations for human and workers' rights, as well as impacts on local communities. However, the perspectives of LAC are often overlooked, as the Battery Passport Steering Committee is primarily composed of lithium-consuming regions (GBA 2019). This oversight can lead to critical issues being ignored and unfair practices persisting. To enhance global lithium resource management, it is crucial to better integrate Latin American stakeholders into the decision-making frameworks. By combining sustainable extraction methods with improved recovery rates and advanced manufacturing capabilities, the LAC region has the potential to shift from a raw material supplier to a global leader in lithium-based products. This approach would not only drive economic growth but also advance sustainability objectives and ensure long-term resource security.

3.3. CO_2, water, and land footprints assessment for lithium in LAC by 2050

Fig. 4 presents an environmental assessment of the CO_2, water, and land footprints linked to lithium extraction in Argentina, Chile, Bolivia, and Brazil. It focuses on the mid-production pathway under two technological scenarios extending through 2050 (SI-3.3).

According to our projections, CO_2 emissions are expected to reach 5.8 Mt in 2050 under the TFS, with Chile, Argentina, and Brazil contributing 37 %, 28 %, and 26 % of that total. In contrast, the TES is projected to reduce CO_2 emissions to 3.3 Mt by 2050, with Brazil being the largest contributor at 35 %, followed by Chile and Argentina at 32 % and 25 %, respectively. While CO_2 emissions under TFS correlate with production volumes, TES achieves reductions through improved efficiency in extraction methods. Brazil's hard rock processing contributes significantly more to emissions than brine extraction. From 2023 to 2050, 27-year cumulative CO_2 emissions are estimated at 96 Mt under TFS and 67 Mt under TES, reflecting a 30 % reduction. A cumulative TFS and TES comparison (Fig. 4c) achieves the highest reduction potential at 42 %, while Brazil records the lowest reduction potential at 16 %.

Water use under the TFS is projected to reach 338 Mm^3 in 2050, with cumulative consumption exceeding 6 Giga cubic meters (Gm^3). In contrast, under the TES, water use could decrease to 198 Mm^3, with cumulative consumption lowering to 4.6 Gm^3—representing a 23 % overall reduction. This decline is driven by advancements in brine extraction processes and the adoption of DLE technology. However, the DLE process also has a disadvantage, which increases freshwater use by 433 Mm^3 for 27 years' cumulation, partially offsetting the reductions achieved. When analyzing the data on a country-specific basis, Brazil shows the largest relative reduction potential at 35 %, attributed to improvements in freshwater efficiency during spodumene concentration (Fig. 4f). Meanwhile, Chile records the largest absolute reduction potential (829 Mm^3) attributed to improved efficiency in the water use of brine and freshwater in the extraction process.

By 2050, land occupation is projected to reach 2784 km^2 under the TFS scenario, reflecting the stock of use land for evaporation and chemical processes. Chile accounts for the largest share (69 %). The TES implementation significantly mitigates this impact, reducing the affected land area to 810 km^2, saving by 1973 km^2, an area nearly the size of Mexico City. While TES leads to a notable overall reduction, Bolivia's share of land occupation increases to 14 %. Chile sees the largest decrease, with a reduction of 76 %, dropping from 1919 km^2 to 455 km^2, amounting to a reduction potential of 1465 km^2 between 2023 and 2050 (Fig. 4i).

Comparative analysis reveals the environmental trade-offs between extraction technologies. If extracting the same amount of lithium through hard rock mining, it would result in over 228 Mt CO_2 expected from 2023 to 2050, but saving around 5 $Gm^3$of total water in the process and 2488 km^2 of land during the same period, highlighting the trade-offs between extraction methods.

A sensitivity assessment reveals that the main source of uncertainty arises from the LCA factors applied to brine-based production, as they rely on averages from existing research studies and different brine operations. Similarly, LCA data for Brazil's emerging hard-rock sector carries uncertainty as it was adapted from Australian hard-rock mining data. While the LCA factors for Brazil carry uncertainty, the yield data for Brazilian spodumene deposits are of high confidence.

By contrast, brine data from current producers such as Chile and Argentina are well-documented and therefore considered high confidence. Bolivia, however, remains an exception: its production pathways are uncertain, and projections were adapted to a best-case scenario assuming the adoption of DLE from 2025 onward, resulting in medium uncertainty. Consequently, the main uncertainty in our model arises from the environmental profiles of brine operations and assumptions for emerging producers, whereas data for established production pathways and Brazilian mineral yields are comparatively robust. Regarding the

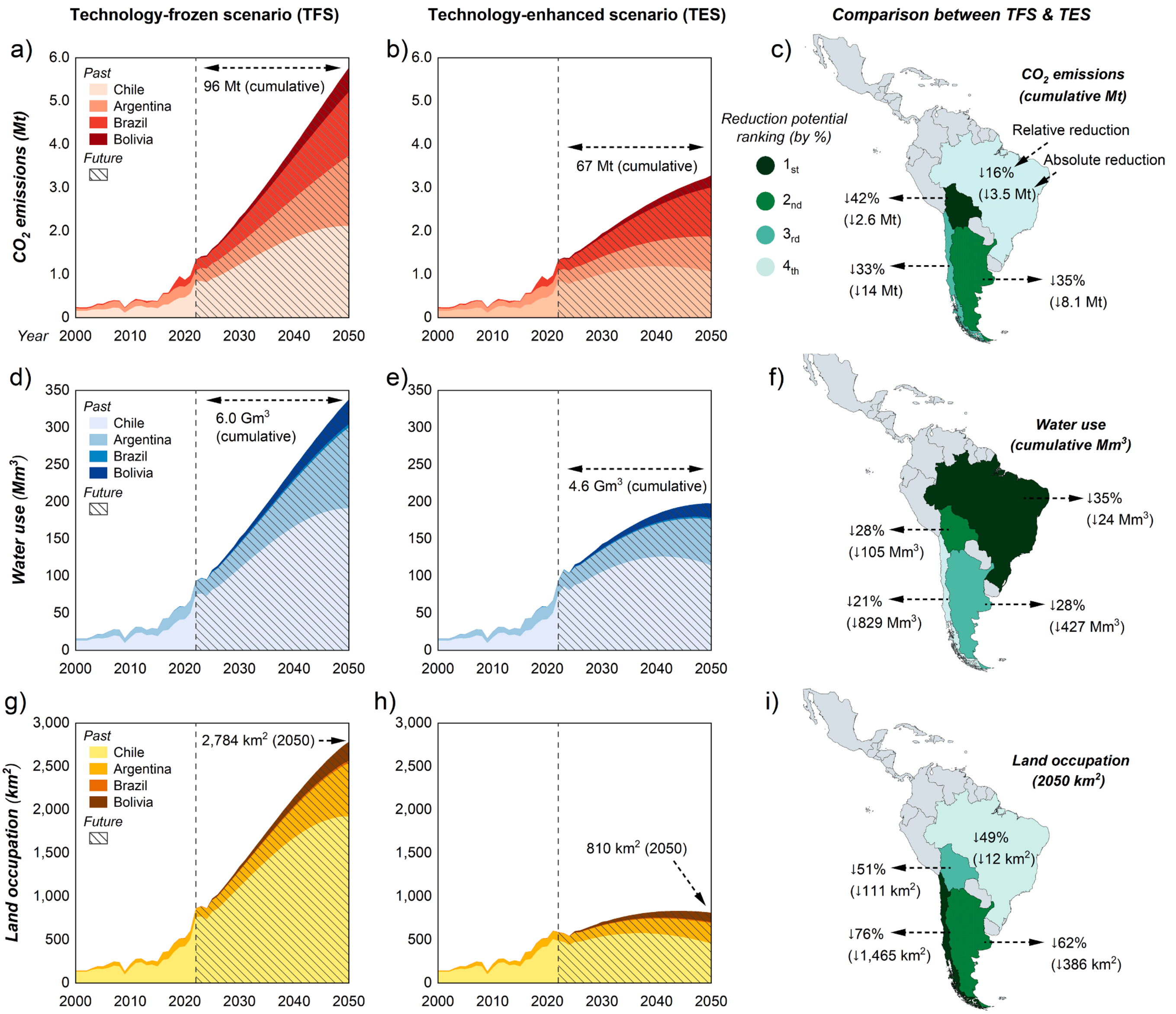

Fig. 4. CO_2, water, and land footprint trends for lithium production in LAC. The environmental impacts of lithium production from brines and spodumene in the Lithium Triangle and Brazil are assessed, considering the period from 2000 to 2022 and forecasting through 2050 under two scenarios: TFS and TES. CO_2 emissions are assessed in panels a), b), and c) showing a cumulative comparison among scenarios and (Mt of CO_2 eq/ton of Li_2CO_3). Water use is assessed in d), e), and f) presenting a cumulative comparison among scenarios and countries (Mm^3/ton of Li_2CO_3). Land occupation is assessed in g), h), and i) land occupation comparison among scenarios and countries (km^2/annual production ton of Li_2CO_3). Further details on environmental impact factors are in Figs. S17–S20.

margin of error, this aspect was incorporated into our estimations by adopting a balanced approach. Rather than relying on extreme assumptions (best- or worst-case values), we based all model inputs on averages across scenarios. This method reduces bias and provides a representative central tendency of the potential outcomes.

A sustainable and fair energy transition requires the responsible expansion of mining operations while safeguarding environmental integrity (S IEA 2024, IRENA 2024). In Latin America, the environmental footprint assessment of lithium extraction reveals that although brine-based methods emit less CO_2 compared to spodumene mining, it imposes a disproportionate local pressure, demanding substantial water and land resources in fragile ecosystems. This situation leaves the region bearing the localized environmental cost of extraction, while the economic benefits from the battery value chain are captured elsewhere. While DLE technology reduces brine water consumption and evaporation losses, it still relies heavily on freshwater, posing a challenge in arid regions like the Lithium Triangle (Vera et al., 2023, Mousavinezhad et al., 2024). In Chile, copper and lithium extraction has faced criticism for depleting groundwater in the Atacama Desert, degrading ecosystems, and transforming meadows and lagoons into salt flats (Kelly et al., 2021, Lagos et al., 2024, Maxwell and Mora, 2020). Therefore, the DLE process should prioritize freshwater re-circulation to minimize usage in water-scarce areas, and the discharge should be treated to meet wastewater discharge standards. DLE technology significantly reduces land use compared to conventional brine evaporation methods, helping to safeguard biodiversity in high Andean wetlands and salt flats. These habitats are vital for species such as Wilson's Phalarope and Chilean flamingos, which depend on brine pools for feeding (Vera et al., 2023, Sanchez-Lopez, 2023, Bustos-Gallardo et al., 2021). Adopting such measures in favor of sustainable mining practices are essential to ensure that global progress towards net zero does not come at the expense of local environmental integrity and social well-being.

4. Conclusion

Latin America's pivotal yet imbalanced role in the global lithium supply chain underscores the distinction between resource wealth and value chain participation. The region is poised to be a primary supplier of lithium raw materials, yet it captures a minimal fraction of the total value generated, which is focused predominantly on downstream stages like refining and battery manufacturing. This imbalance reflects not only the economic competitiveness of established hubs such as China but also the absence of coordinated regional strategies that could enhance bargaining power and industrial upgrading. Without a shift from fragmented national initiatives to collective action, Latin America risks remaining locked into the role of raw material exporter in the energy transition.

Environmental projections reveal that brine-based extraction—despite lower CO_2 emissions—imposes significant pressure on water and land resources, especially in the Lithium Triangle. Although emerging technologies such as DLE can mitigate some impacts, their implementation must be accompanied by robust governance, shared basin-level water management, and stronger community engagement to secure long-term legitimacy. In terms of circularity, lithium in-use stocks are projected to grow substantially by 2050, particularly in countries like Brazil and Mexico. However, current recycling rates remain low, EOL battery flows are still limited, and recovery technologies are still evolving. Nevertheless, the importance of developing localized recovery systems and coordinated regional strategies remains essential. While recycling will play a crucial long-term role, improving recovery in primary extraction in Brazil appears more impactful in the near term. By aligning sustainable extraction practices with investment in recovery and manufacturing, Latin America has the potential to evolve from a resource supplier to a key player in the global lithium value chain—contributing not only to economic growth but to a more equitable and environmentally responsible energy transition.

CRediT authorship contribution statement

Estefanía Orquera: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Guochang Xu:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Tim Werner:** Writing – review & editing, Supervision, Methodology. **Stephen Northey:** Writing – review & editing, Supervision, Methodology. **Oscar Tiku:** Writing – review & editing, Supervision, Methodology. **Damien Giurco:** Writing – review & editing, Supervision, Project administration. **Kazuyo Matsubae:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108677.

Additional information on lithium flows and stocks in Latin America from 2000 to 2050 is provided. Tables and Figures show the scenario setting and lithium assessment in the lifecycle of lithium in the region.

Data availability

Data will be made available on request.

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