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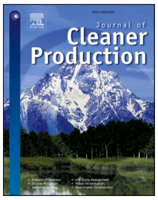

Constructing a life cycle inventory of Spodumene concentrate production: Greenbushes case, Western Australia

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ABSTRACT

Life cycle assessment (LCA) is a data-intensive method widely used by academics and professionals to facilitate environmental decision-making and policy formulation. However, LCA's effectiveness can be compromised by the lack of high-quality data and significant data gaps in the life cycle inventory such as for the LCA model of lithium extraction in the mining industry. While lithium has become the focal point in the clean energy transition, oversimplified models and approximations from other sectors have diminished the quality of input and output data. This research aims to model the mining and processing operations in the world's largest lithium mine in Greenbushes, Australia, by utilising first-hand data and production statistics to increase the accuracy and transparency for stakeholders. The results demonstrate a 36.8% and 30.6% reduction in carbon dioxide equivalent emissions for lithium carbonate and lithium hydroxide monohydrate production, respectively, using this study's modelled Spodumene concentrate compared to previous studies for lithium compound production. Additionally, the study reveals that improved grinding technologies in the newer plant (CGP2) of Greenbushes have reduced the overall global warming potential impact category of Spodumene production by 17.3% using high-pressure grinding rolls (HPGR). It is crucial to note that the highest contributor to the carbon footprint in the processing plant is electricity usage, while in mining operations, blasting is the primary contributor.

1. Introduction

Electric vehicles and battery manufacturing play a crucial role in addressing the challenges of climate change (Rutovitz et al., 2020; Langdon et al., 2022). Based on the IEA report, by 2030, about 33% of cars in China and 20% of vehicles in Europe and the USA will be electric, which avoids at least 6 million barrels of oil per day; subsequently, this will avoid more than 10 million barrels of oil per day in 2035 (IEA, 2024). The replacement of fossil-based energy is enabled by metals and minerals (Khakmardan et al., 2023a). However, some are critical for economic or strategic aspects, like lithium, the "white gold" of this era (Allam et al., 2022; Khakmardan et al., 2023b). Lithium had a 13-fold production growth from 2003 to 2023 due to the shift to clean energy generation technologies (Jaskula, 2007, 2011, 2015, 2018; Sterba et al., 2019). Market projections show another ten times in lithium production growth will happen by 2050 compared to 2023, on the road to net zero (IEA, 2024; Jaganmohan; Source, 2022). This caused unconventional lithium resources to become feasible, resources that have less lithium content and more complex textures (Khakmardan et al., 2024a).

LCA is widely used to identify and mitigate the environmental burdens of the minerals industry during the energy transition. LCA evaluates the environmental impacts of a process or product using a systematic method (Hollberg, 2016; Hauschild et al., 2018; Guiné et al., 2002). However, most of the existing LCA models for lithium production assessment use Spodumene production, and lithium brine inspissation flows from the Ecoinvent database. Spodumene production flow is approximated from iron ore mining and lime comminution (Sutter, 2007; Althaus et al., 2007). This raises concerns about the accuracy of LCA results for other projects.

As stated in the administrative information of the Ecoinvent database, the Spodumene production flow was initially constructed by Roland Hischier in 2007, using approximations based on iron ore mining and limestone crushing to estimate water, heat, and electricity consumption (Frischknecht et al., 2007). In 2012, Anna Stamp et al. further developed this model by employing copper mining as a proxy for land transformation and disturbance using iron ore mining as a proxy for

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diesel and blasting flows (Stamp et al., 2012). For electricity and grinding, they used manganese beneficiation, while chemical inputs were based on rough values from Garrett's 2004 handbook on lithium extraction. Despite its limitations, this model was considered the most accurate life cycle assessment (LCA) model for lithium mining for several years and has been cited by numerous scholars.

However, critics argue that the input-output data of this model is imprecise, relying on approximations from iron ore mining and manganese beneficiation. Notably, Ambrose et al. (2020) and Manjong et al. (2021), along with other publications, used Stamp's model as their base case for further research (Ambrose et al., 2020; Manjong et al., 2021). Due to several areas of improvement, particularly in the assumptions and data gaps, Jiang et al. (2020) used Gabi 8.1 to construct a Spodumene (RER) flow, developing a lithium carbonate flow with primary data collected in 2014 (Jiang et al., 2020). This model became the basis for lithium carbonate flows from hard rocks in Ecoinvent.

However, access to the detailed input-output data of the Spodumene production flow used in this model is unavailable, and it refers to "RER" (Rest of Europe), indicating that the flow was designed for European conditions, which do not accurately reflect the actual mining processes in Australia, where the Australian grid mix should be used. To address these gaps and study limitations, Kelly et al. (2021) attempted to improve LCA models for lithium carbonate and lithium hydroxide monohydrate production from both ore and brine sources (Kelly et al., 2021). However, the assumptions made in this study did not align with the realities of Spodumene mining and processing in Australia, which at that time was the world's sole supplier of Spodumene. Furthermore, the mining and processing stages were not fully covered, and the model heavily relied on assumptions rather than high-quality primary data.

In 2022, Chordia et al. developed LCA models for emerging Spodumene mines in Finland and Canada, as well as an existing project in Australia (Chordia et al., 2022). For Spodumene production flow in Australia, Chordia reused the same input-output data from Kelly's model, which was based on assumptions rather than real data. The only significant difference in Chordia's lithium hydroxide monohydrate inventory was the chemical and water consumption compared to Kelly's, with the quantities of concentrate and energy remaining the same as in the previous model.

Almost all previous studies did not cover all stages of Spodumene production flow in their study, and data gaps and incompleteness are evident in their models (Rolinck et al., 2023). This poses a significant risk to policymakers and decision-makers who depend on critical LCA data to drive sustainability improvements. A detailed comparison of the input-output data from these key studies is presented in Table 1, summarising the differences between them, and explaining the reasons for the variations in their final results.

With all the research mentioned above, the question of the true environmental burdens of the current technologies associated with the production and utilisation of critical minerals from lower-grade resources, as well as real-world cases, remains unresolved. Therefore, this paper aims to construct the life cycle inventory (LCI) of Spodumene concentrate production based on data from the Greenbushes mine in Australia, the largest Spodumene mine in the world, accounting for 25% of total annual lithium and 42% of total Spodumene production. With the current planning, this project is scheduled to produce Spodumene concentrate till 2042; however, another plan is under study to extend the project lifetime to 2055 (SEC Technical Report Summary, 2022). Additionally, the global warming impact category values from referenced studies are compared with this detailed model in the sensitivity analysis section to demonstrate the significance of high-quality LCI developed with primary data.

This paper is organised into four main sections: section 1 provides the overall view of the study in conjunction with an extensive critical literature review; section 2 is dedicated to the data gathering, LCI development, and LCA modelling method. Section 3 is heavily focused on the impact assessment analysis and interpretation of the results by using different methods, including hotspot analysis and sensitivity analysis. Finally, section 4 explains the current work limitations and concludes the study with a few recommendations for future research.

2. Data and method

This comprehensive LCA study follows the ISO 14040 standard, which consists of four phases: goal and scope definition, Life Cycle

Table 1
– Inputs and outputs of the production of one tonne of Spodumene concentrate.

	Unit	R Hischier	A Stamp et al.	J Kelly et al.	M Chordia et al.
Year		2007	2012	2021	2022
Background		Ecoinvent 2	Ecoinvent 2.2	Ecoinvent 3.1	Ecoinvent 3.8
Inputs					
Blasting	kg	0.27	0.84	–	–
Conveyor belt	m	0.000028	–	–	–
Diesel	MJ	25.5	78.9	4500	4500
Electricity	kWh	33.9	11.8	–	–
Heat	MJ	92.62	–	–	–
Industrial machine	kg	0.23	–	–	–
Mine infrastructure	item	0.0000000008	0.00000005	–	–
Occupation land	m^2*a	0.12	0.201	–	–
Recultivation, iron mine	m^2	0.0021	0.0054	–	–
Spodumene in ground	tonne	1.1	–	4.5	4.5
Lithium in ground	kg	–	49.9	–	–
Transformation from forest	m^2	0.0021	0.0067	–	–
Transformation to mineral extraction site	m^2	0.0021	0.0067	–	–
Water	m^3	0.0293	2140	3	3
Fatty Acids	kg	–	1.88	–	–
Steel	kg	–	0.802	–	–
Sodium carbonate	tonne	–	–	0.015	0.015
Outputs					
Spodumene	tonne	1	1	1	1
Particulate <2.5	kg	0.15	0.446	–	–
Particulate >10	kg	1.45	4.46	–	–
Particulate >2.5 - <10	kg	1.31	4.02	–	–
Water	m^3		–	–	–
Waste heat	MJ	–	42.3	–	–

Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA), and interpretation. The following subsections are organised accordingly.

Given the focus of the paper on constructing the LCI for Spodumene concentrate production, precise identification and quantification of input-output flows for the SC6 production are described in the LCI development section.

2.1. *Goal and scope*

The primary goal of this study is to measure the environmental impacts of the production of one-tonne Spodumene concentrate (known as SC6) in the Greenbushes plant, Australia, in the year 2022 with high precision and based on primary data. So, in order to increase the data quality and decrease data gaps, a considerable effort was invested in LCI development of Spodumene mining and processing operation units and their related missing mining background flows in the utilised database. The functional unit is considered a one-tonne Spodumene concentrate with 6% Li_2O content. The scope of the study is from the mine to the final door of the plant (cradle-to-gate). It covers all stages of the mining and processing operations, including overburdening, drilling and blasting, loading and hauling, maintenance, auxiliary operations and infrastructure at the mine site, besides crushing and screening, grinding and classification, material handling, gravity and magnetic separation methods, flotation, filtration and dewatering, tailing management, reagents preparation unit and infrastructure in the processing plant. Fig. 1 depicts the study system boundary. Notably, Tantalum concentrate is a by-product of the processing operation; however, its weight ratio compared to SC6 is as low as 0.23%, which is negligible, and consequently, it is excluded in the final LCIA, and no allocation is included in this LCA.

2.2. *Life cycle inventory*

The following formulas and methods were applied to each of the inputs listed in Table 2. After extracting mine design parameters and historical production data from the 2022 sustainability and technical reports of the Greenbushes project, the inputs and outputs of the Spodumene production process were identified and categorised into the clusters described below (Ingham et al., 2011, 2012; Greig et al., 2018; Talison Lithium, 2022).

2.2.1. *Minerals to products balance*

The Greenbushes deposit features a main rare-metal zoned pegmatite and numerous more minor pegmatite dykes and footwall pods. The Lithium zone is rich in Spodumene minerals. Spodumene is selected as the ore input flow for this model. The host rocks, consisting of granofels, ultramafic schists, and amphibolites, represent the waste stream. Consequently, basalt is chosen as the elementary flow for the waste stream.

According to primary data, 1,348,616 metric tonnes of SC6 and 3188 metric tonnes of tantalum concentrate (by-product) were produced in 2022. Additionally, 12,657,877 metric tonnes of waste and 4,189,513 metric tonnes of tailings were generated (Talison Lithium, 2022). The total amount of ore processed is calculated by summing the product, by-product, and tailings, resulting in 5,541,317 metric tonnes. This gives a waste-to-ore ratio of 2.28.

2.2.2. *Materials and chemicals*

The only materials directly used in the mining operation are explosives for blasting. For the calculation of the total amount of explosives needed per functional unit (one tonne SC6), Equation (1) has been utilised, where E_x is the total amount of explosives per functional unit. Also, d_e is the density of the explosive, d_i *and* d_j are, respectively, the blasting-hole diameter for ore and waste blocks, T_j is the hole stemming factor, d_o and d_w is the density of ore and waste respectively, H_o and H_w are the height of ore mine forefront bench and waste bench respectively, B is the burden of blasting design, L_i and L_j are the blast-hole length for ore and waste respectively, and S is the spacing between blasting holes. In addition, WO is the waste-to-ore ratio, and F_f is the average amount of needed ore per tonne of SC6. These values are calculated based on formulas in the handbooks and based on mine design parameters from the technical reports (Ingham et al., 2012; Hustrulid et al., 2013; Darling, 2011).

$$Ex = \left(\left(\frac{de*1000*di*Tj*Li}{do*Ho*B*S}\right) + \left(WO*\left(\frac{de*1000*dj*Tj*Lj}{dw*Hw*B*S}\right)\right)\right)*Ff$$

Equation 1)

In the processing operation, there are several consumables as materials and chemicals, including steel balls as grinding media (GM) for the comminution operation, ferrosilicon (FeSi) as dense media for the gravity separation operation, sodium hydroxide (NaOH) and soda ash (Na_2CO_3) as pH adjustment agent, propylene glycol ($C_3H_8O_2$) as a frother, oleic acid ($C_{18}H_{34}O_2$) as the collector for the flotation operation, and polyacrylamide ($(C_3H_5NO)_n$) as flocculant for the dewatering operation; The method for calculating these materials and chemicals was using directly recorded data from the industry during the site visit

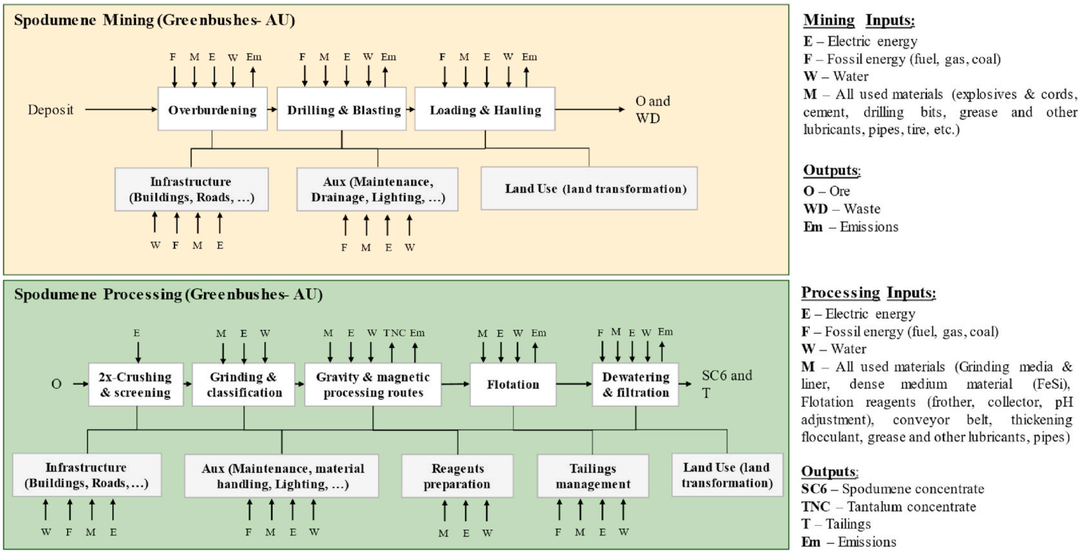

Fig. 1. Study system boundary.

Table 2
Greenbushes LCI in 2022, MS = mining stage, PS = processing stage (Ingham et al., 2009, 2010, 2011, 2012; Greig et al., 2018; Talison Lithium, 2022).

System Inputs	Value	Unit	System outputs	Value	Unit
Materials and chemicals			**Product**		
Blasting [MS]	4.75E+00	kg	Spodumene concentrate (SC6)	1.00E+00	t
Oleic acid [PS]	2.20E+00	kg	**By-product**		
Propylene glycol [PS]	2.20E-01	kg	Tantalum concentrate	2.36E-03	kg
Soda ash [PS]	1.22E+00	kg	**Wastes**		
Sodium hydroxide [PS]	3.41E-04	kg	Tailings	3.08E+00	t
Polyacrylamide [PS]	2.45E-01	kg	Waste rock	9.33E+00	t
Grinding media [PS]	1.56E+01	kg	Tantalum, in-ground	4.18E-01	kg
Dense media [PS]	4.84E-01	kg	Scrap steel	4.58E-01	kg
Grinding media manufacturing [PS]	1.56E+01	kg	Waste electric and electronic equipment (WEEE)	8.89E-02	kg
Conveyor belt [PS]	3.91E-04	m	**Emissions to air**		
PE pipe [MS]	8.10E-04	m	Carbon monoxide	2.18E+02	g
PE pipe [PS]	3.72E-04	m	Nitrogen oxides	3.73E+02	g
Mineral resources			Particulates, <2.5 um	2.42E+01	g
Basalt [MS]	9.33E+00	t	Particulates, >10 um	7.93E+02	g
Spodumene [MS]	4.11E+00	t	Sulphur dioxide	2.63E-01	g
Tantalum, in the ground [MS]	4.20E-01	kg	VOC, volatile organic compounds	2.73E+01	g
Energy consumption			Water (gas)	6.86E-01	m^3
Electricity, medium voltage [PS]	4.61E+02	MJ	**Emissions to water**		
Gas and oil consumption			Water (liquid)	1.84E+03	kg
Diesel [MS]	1.44E-01	MJ			
Diesel [PS]	4.86E+02	MJ			
Liquified petroleum gas [PS]	4.97E+01	MJ			
Transportation					
Transport by mining truck [MS]	6.79E+01	t*km			
Blasthole drilling [MS]	3.25E-01	m			
Excavation by mining excavator [MS]	4.83E+00	m^3			
Infrastructure					
Building (hall) [MS]	3.09E-04	m^2			
Building (multi-storey) [MS]	4.36E-03	m^3			
Building (hall) [PS]	1.20E-03	m^2			
Building (multi-storey) [PS]	2.20E-02	m^3			
Mining road construction [MS]	1.75E-02	m*a			
Mining road maintenance [MS]	1.75E-02	m*a			
Land use					
Occupation, mineral extraction site [MS]	4.06E+00	m^2*a			
Transformation from forest [MS]	1.88E-01	m^2			
Transformation to mineral extraction site [MS]	1.88E-01	m^2			
Occupation, industrial area [PS]	5.54E+00	m^2*a			
Transformation from forest [PS]	6.40E-02	m^2			
Transformation to an industrial area [PS]	6.40E-02	m^2			
Water consumption					
Water (decarbonised) [MS]	4.30E-01	kg			
Water (harvested from rainwater) [MS]	6.86E+02	kg			
Tap water [PS]	2.12E+01	kg			
Water (harvested from rainwater) [PS]	1.84E+03	kg			

and interview; also the range of variation of these consumables is checked at site and tested in the sensitivity analysis.

Regarding water consumption in drilling operations, the amount of water used for blast-hole drilling is calculated based on the equipment catalogue. Also, for dedusting purposes in mining and processing operations, the amount of water consumed is collected from the sustainability report.

2.2.3. Energy consumption

Direct electricity consumption in the mining operation is primarily attributed to water drainage from the pits. Also, the main energy source for the processing operation is the electricity purchased from Australia's grid mix (representing the Australian average grid mix). This electricity consumption is recorded from the primary data source and divided by the total amount of SC6 products in 2022.

In the mining operation, direct diesel consumption in LCI is limited to mobile projectors used for lighting and safety during night operations. Diesel consumption for loading, hauling, and drilling is calculated separately in their respective sections.

The direct diesel consumption calculation method can be seen in Equation (2), where D_{2m} represents diesel consumption for lighting purposes per functional unit, G_L is the total area of mining operation, P_a is the effective lighting area, P_c is projector fuel consumption per hour, N_t is average nighttime, and M_O is the total amount of exploited ore in the year (2024 Sun Graph for Greenbushes, 2024).

$$D_{2m} = \left(\frac{GL}{Pa}\right) * \left(\frac{Pc*Nt}{Mo}\right) *Ff \qquad \text{Equation 2)}$$

For processing operations, there are a number of construction equipment, vehicles, and auxiliary activities like dryers at the TGP plant that consume diesel and other fuel types, including liquified petroleum gas (LPG). These values are directly reported in the primary data and divided and used in the model after subtracting the mining machinery demanded by diesel (Neale, 2001).

2.2.4. Mining activities

Equation (3) was used for the drilling operation, where *D* was the needed drilling length per tonne of functional unit (SC6). These values are calculated based on formulas in the handbooks and based on mine design parameters from the technical reports (Ingham et al., 2012; Hustrulid et al., 2013; Darling, 2011).

$$D = \left(\frac{Li}{do * Ho * B * S} + \frac{Lj}{dw * Hw * B * S} \right) * Ff \qquad \text{Equation 3)}$$

For the loading operation, the mining excavator needs to load ore, waste, and overburden. Equation (4) was used to calculate the amount of loading (m^3) per functional unit. Where L is the total loading per functional unit, and SO is the calculated stripping-to-ore ratio.

$$L = \left(\frac{1}{do} + \frac{WO}{dw} + \frac{SO}{ds} \right) * Ff \qquad \text{Equation 4)}$$

In order to calculate the amount of transportation (t.km), Equation (5) has been used.

$$Tr = \left(\frac{Mo * Lo}{Mo} + \frac{Mw * Lw}{Mo} + \frac{Ms * Ls}{Mo} \right) * Ff \qquad \text{Equation 5)}$$

where T_r is the total transportation per tonne of spodumene ore, M_o, M_w, and M_s are, respectively, the total weight of transported ore, waste and overburden in that year; also, L_o, L_w and L_s are, respectively, the average of two-way (go and return) length of ROM, waste dump, overburden roads, which is measured by utilising Google Earth Pro 7.3.6.9796 satellite imagery.

2.2.5. *Land use*

Land use (L_u) and land transformation (L_t) are the other flows that represent the land disturbance and land transformation in the year 2022. These flows are calculated based on the Khakmardan et al., 2024 method (Khakmardan et al., 2024b). The transformed land type in the year 2022 is calculated by the difference of total surface area in 2022 to 2021 divided by the total exploited ore in 2022. ΣGL is the accumulated measured surface area of the mining and processing areas in the year 2022 by utilising Google Earth Pro 7.3.6.9796 satellite imagery. The amount of land use and land transformation is presented in Equation (6) and Equation (7).

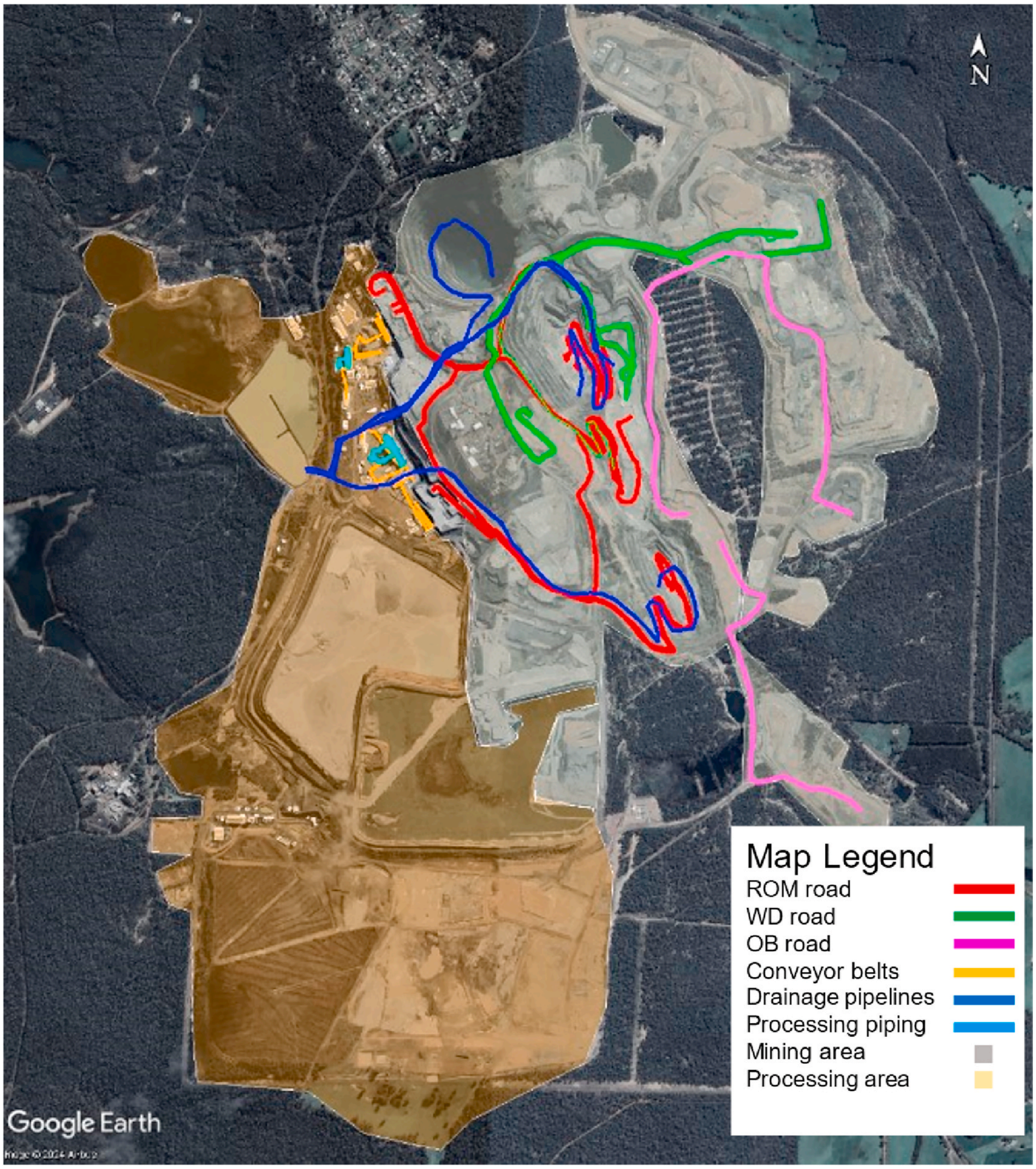

Fig. 2. Aerial satellite photos of Greenbushes mining and processing operations.

$$Lu = \left(\frac{\Sigma GL2022}{Mo}\right) * a \qquad \text{Equation 6)}$$

$$Lt = \left(\frac{\Sigma GL2022 - \Sigma GL2021}{Mo}\right) \qquad \text{Equation 7)}$$

2.2.6. Equipment and infrastructure

Buildings, road construction, and maintenance are considered primary infrastructure. Additionally, industrial machinery and specialised activities are considered capital equipment in the mining sector, including blast-hole drilling and excavation by mining excavators. Fig. 2 shows the mine boundaries (light grey) and processing-related area boundaries in 2022 (light yellow) on the left side. Also, in this figure, run-of-mine (ROM) routes, waste dump routes (WD), and overburdening depot roads (OB) are shown respectively with red, green, and pink lines. Also, conveyor belts and processing piping systems, besides the drainage pipeline, are shown in this figure.

The area of the buildings is measured using the same method as quantifying road lengths via satellite imagery. Then, based on the Australian National Construction Codes (NCC) and International Construction Code (IBC), the average height and number of floors for mining workshops, processing plants, and office buildings are calculated (Board, 2015; (ICC) and I.C.C., 2018).

B_s in Equation (8) refers to building hall input flow, where M_{ct} is the total amount of produced concentrate in the processing section during the lifetime of the project from 1983 to the projected year of 2042; this is the same for M_{ot} as the total amount of exploited ore in the lifetime of the mine. G_{Em}, G_{Ep}, and G_{Ea} are, respectively, the surface area of buildings for mining workshops, processing plants, and administration office buildings. Also, $B_{v,}$ in Equation (9), refers to building multi-storey input flow, where H_m, H_p and H_a are, respectively, the average height of mining workshop buildings, processing plant buildings, and administration buildings.

$$Bs = \left(\left(\frac{GEm + GEa}{Mot}\right) * Ff\right) + \left(\left(\frac{GEp}{Mct}\right)\right) \qquad \text{Equation 8)}$$

$$\begin{aligned} Bv = {} & \left(\frac{(GEm * (Hm)) + (GEa * (Ha\,))}{Mot} * Ff\right) \\ & + \left(\frac{(GEm * (Hm) + (GEp * (Hp) + (GEa * (Ha\,)}{Mct}\right) \qquad \text{Equation 9)} \end{aligned}$$

Equation (10) was used to calculate the amount of road construction and maintenance. Where R_t (R_m) is the amount of road construction (R_m for the road maintenance), R_o, R_w, and R_s are the average measured length of ore road, waste dump road, and overburden road from satellite imagery.

$$Rm = Rt = \left(\left(\frac{\Sigma Ro + \Sigma Rw + \Sigma Rs}{Mo}\right) * Ff\right) \qquad \text{Equation 10)}$$

For the PE pipe demand in the mining operation, it is estimated that 10% of the piping length requires replacement annually due to depreciation, based on data from similar industrial and mining projects (Consultants and H.B.E.). This annual replacement is proportionally allocated according to the total ore mined in 2022, and the calculated figure is then used to determine the specific quantity of PE pipe required per tonne of ore to produce one tonne of SC6. Satellite imagery is employed to measure the piping distance between the pit and water reservoir ponds, and alternative scenarios are explored in the sensitivity analysis.

Conveyor belts and pipes for material handling and pulp transportation are similarly calculated using approximated satellite imagery measurements, with depreciation rates of 5% for conveyor belts and 10% for pipes, in line with other processing projects (Consultants and H. B.E.).

Due to the incomplete coverage of mining operation flows in the ecoinvent database, it was necessary to construct several missing mining background flows. These included blast hole drilling using an Epiroc D65 rig, hauling with a CAT 777 mining truck, excavation by a CAT 6015 excavator, mine road construction, and road maintenance. To address these gaps, the required flows were developed using a combination of primary data, which included technical specifications and fuel consumption details, alongside whitepapers that provided practical fuel consumption data from various case studies. Additionally, elementary flows were approximated using existing ecoinvent data from related processes, such as hauling with a 40-tonne lorry, manufacturing of a 40-tonne lorry, hydraulic digger manufacturing, excavation by hydraulic digger, building machine manufacturing, and road maintenance and construction (Neale, 2001; Caterpillar; TRICO; Kirtley et al., 1998; Marketing, 2024; Marketing and V.G., 2021; Marketing and V.G., 2020; Marketing and V.G., 2019a; Marketing and V.G., 2019b; Marketing and V.G., 2019c; Marketing and V.G., 2019d; Marketing and V.G., 2018; Marketing and V.G., 2017; Caterpillar and CAT 785 Mining Truck, 2023; Caterpillar and CAT 777 Water Solutions Truck, 2022; Caterpillar and CAT 6015 Hydraulic Mining Shovel, 2021; Caterpillar and CAT D9 Dozer, 2020; Caterpillar, 2020; Caterpillar and Clifton, 2017; Caterpillar and CAT 6020B Hydraulic Mining Shovel, 2015; Caterpillar and CAT 16M Motor Grader, 2015; Caterpillar and CAT 777F Off-Highway Truck, 2010; AB, 2023; Machinery, 2023; Westrac, 2018; Capik et al., 2021).

This approach ensured that all key processes in the mining operation were comprehensively modelled, resulting in a more accurate and complete life cycle inventory for the Spodumene production process. Detailed input-output flows for these mining machinery and operations are summarised in the supplementary file 1 (SI-1).

3. Results and discussion

3.1. LCIA results

The LCIA was conducted using the ReCiPe midpoint (H) 2016, normalised by the World (2010) method. The LCIA results for one tonne of Spodumene concentrate with 6% Li_2O content are outlined in Table 3 for different categories of this assessment method. Additional environmental impact assessment methods for Spodumene concentrate production, are comprehensively summarised and documented in the supplementary file 2 (SI-2).

Table 3
LCIA result of one-tonne Greenbushes spodumene ore and concentrate.

Impact category name	Ore	SC6	Unit
Fine particulate matter formation	8.14E-02	9.79E-01	kg $PM_{2.5}$ eq
Fossil resource scarcity	2.05E+00	8.09E+01	kg oil eq
Freshwater ecotoxicity	6.36E-01	2.41E+01	kg 1,4-DCB eq
Freshwater eutrophication	1.87E-03	2.61E-01	kg P eq
Global warming potential	1.01E+01	3.23E+02	kg CO_2 eq
Human carcinogenic toxicity	1.07E+00	1.78E+02	kg 1,4-DCB eq
Human non-carcinogenic toxicity	7.75E+00	3.44E+02	kg 1,4-DCB eq
Ionising radiation	1.69E-01	6.89E+00	kBq Co-60 eq
Land use	9.99E-01	5.74E+01	m^2a crop eq
Marine ecotoxicity	8.27E-01	3.22E+01	kg 1,4-DCB eq
Marine eutrophication	3.60E-04	1.97E-02	kg N eq
Mineral resource scarcity	2.23E+01	7.73E+01	kg Cu eq
Ozone formation, Human health	4.40E-01	3.30E+00	kg NO_x eq
Ozone formation, Terrestrial ecosystems	4.48E-01	3.35E+00	kg NO_x eq
Stratospheric ozone depletion	5.13E-05	3.90E-04	kg CFC_{11} eq
Terrestrial acidification	3.05E-01	2.45E+00	kg SO_2 eq
Terrestrial ecotoxicity	4.12E+01	1.73E+03	kg 1,4-DCB eq
Water consumption	6.17E-02	3.88E+00	m^3 eq

3.2. Hotspot analysis

The overall hotspot analysis is summarised in Fig. 3, showing the contribution of each input to its respective impact category. The results indicate that chromium steel as grinding media (GM) used in ore preparation for flotation contributes the most across most impact categories. Flotation, aimed at enhancing grade and recovery, increases the economic value and resource efficiency of the project (Khakmardan et al., 2020; Doodran et al., 2020). This is followed by electricity consumption, mainly used in grinding operations and ore production from mining activities. Diesel usage is another significant contributor, with notable impacts across multiple categories.

Most other flows contribute less than 10% to each impact category. However, the multi-story building flow has a higher contribution to freshwater and marine ecotoxicity, as well as human non-carcinogenic impacts, at 28.9%, 26.9%, and 19.4%, respectively. A distinct trend is seen in the land use and water consumption categories. For land use, oleic acid—a flotation collector—accounts for the largest share (50.2%), followed by tailings output at 26.2%.

Water consumption, on the other hand, shows a different pattern, with direct water input-output flows contributing 47.4%, followed by oleic acid (15.6%), grinding media (14.6%), medium-voltage electricity (7.2%), and Spodumene ore mining (6.5%). All other flows contribute less than 9% to water consumption.

Given the significance of the global warming potential (GWP) impact category, which reflects the carbon footprint of a process or product, a detailed hotspot analysis was conducted to assess the contribution of key flows during mining and processing operations at the Greenbushes plant.

The largest contributor to the GWP of producing one tonne of spodumene concentrate at the Greenbushes plant is electricity consumption, accounting for 39.22% of the total impact, or 126.71 kg CO_2 eq per tonne of SC6 (with a total GWP of 323.07 kg CO_2 eq). This is followed by grinding media (chromium steel forged balls), contributing 25.21%, and direct diesel consumption at 13.65%. The final major contributor is the input of mined Spodumene ore to the processing plant, which encompasses all inputs and outputs of mining activities, contributing 12.90%.

The remaining system inputs, summarised in Table 4, collectively contribute less than 9.10% to this impact category. Based on these findings, several realistic scenarios were explored in the sensitivity analysis to assess the potential variation in impacts due to study limitations.

In the mining operation, producing one tonne of Spodumene ore generated 10.14 kg CO_2 eq in 2022. Of this, 59.00% came from drilling and blasting operations, while 35.83% resulted from loading and hauling activities. The majority of the GWP impact from blasting is attributed to the consumption of explosive chemical ingredients, including calcium nitrate, ammonium nitrate, nitrogen inorganic fertiliser, and aluminium used as casing for explosive boosters, making up 91.9% of the blasting impact. Additionally, 94.37% of the drilling impact stems from direct diesel consumption by the Epiroc drill wagon at the mining site.

For loading and hauling, most of the impact is due to direct diesel consumption by mining machinery (dump trucks and hydraulic excavators), accounting for 50.32% of the total impacts in this category. All other flows in the mining operation collectively contribute less than 5.2% to the GWP impact for Spodumene ore.

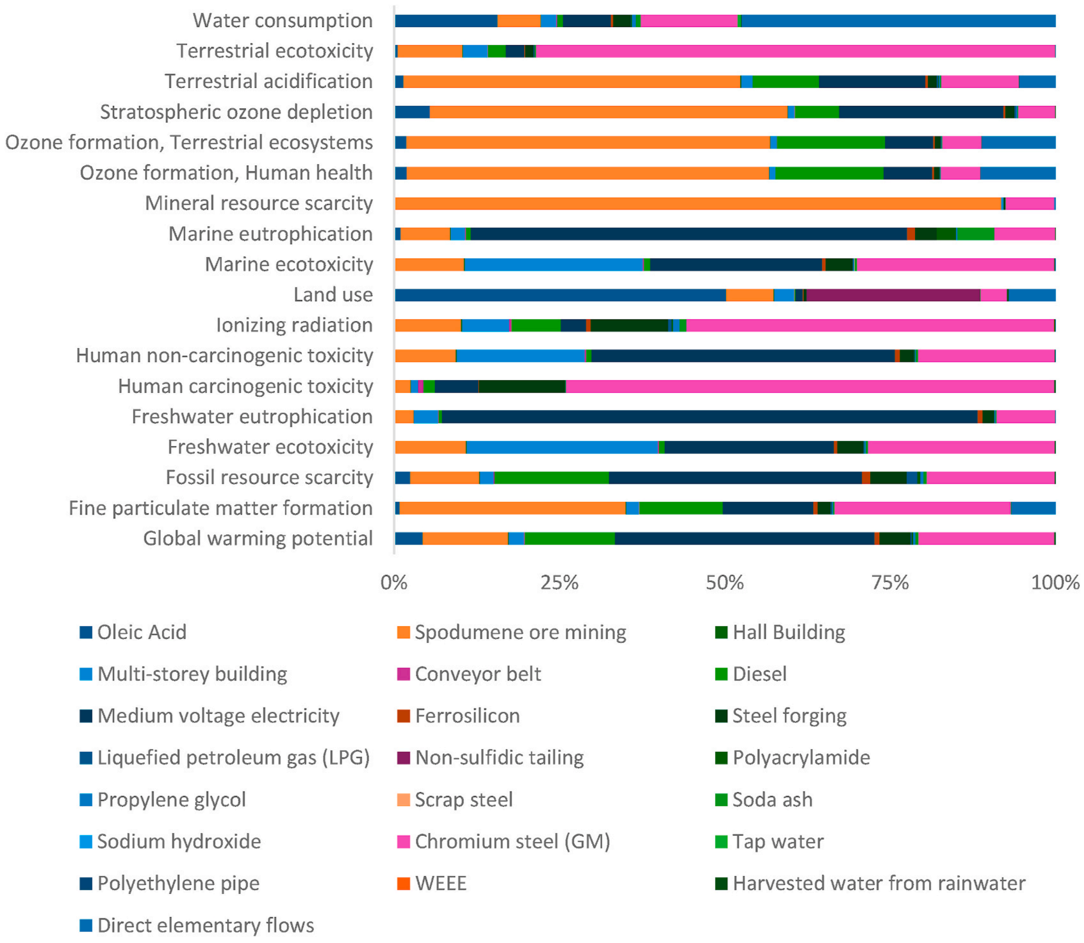

Fig. 3. – Flows contribution tree for the impact categories.

Table 4
Contribution tree of input-output flows of Spodumene concentrate production.

Contribution		Process	Amount (kg CO_2 eq)
100%		1-tonne Spodumene concentrate (SC6)	323.07386
39.22%		Electricity, medium voltage	126.71234
20.53%		Grinding media (Chromium Steel)	66.32494
13.65%		Diesel	44.10596
12.90%		Spodumene ore	41.66668
	6.58%	Blasting with explosives	21.25037
	2.91%	Transport by mining truck	9.41633
	1.71%	Excavation by mining excavator	5.51193
	1.03%	Blasthole drilling	3.33159
	0.45%	Building (multi-storey)	1.44121
	0.08%	Mining road maintenance	0.25449
	0.05%	Water (harvested from rainwater)	0.16581
	0.05%	Mining road construction	0.15986
	0.04%	Building (hall)	0.11348
	0.00%	Diesel	0.01313
	0.00%	Polyethylene pipe	0.00845
	0.00%	Water (decarbonised)	3.645E-05
4.68%		Grinding media manufacturing (Forging)	1.51E+01
4.33%		Oleic acid	13.99078
2.27%		Building (multi-storey)	7.32317
0.76%		Ferrosilicon	2.46436
0.48%		Soda ash	1.56068
0.31%		Propylene glycol	1.00271
0.25%		Polyacrylamide	0.82151
0.20%		Liquefied petroleum gas	0.63549
0.14%		Building (hall)	0.44581
0.14%		Water (harvested from rainwater)	0.44182
0.13%		Conveyor belt	0.41509
0.01%		Tap water	0.02301
0.00%		Waste electric and electronic equipment (WEEE)	0.0048
0.00%		Scrap steel	0.00428
0.00%		Sodium hydroxide	0.00162
0.00%		Polyethylene pipe	0.00042

3.3. Sensitivity analysis

Due to study limitations, such as uncertainty around the exact ferrosilicon (FeSi) loss in the dense medium separation unit, the actual grinding media (GM) loss, and the specific alloy composition of the grinding media, several LCA models were run using primary data and information from mineral processing references (Wills et al., 2015; Aldrich, 2013; Moema et al., 2009). The analysis shows that choosing carbon steel as the primary alloy for grinding balls could reduce the GWP by up to 13.6% per one-tonne SC6. However, this material selection poses technical limitations (Hosseini et al., 2024). However, utilising respectively ferromanganese alloy steel and ferromanganese-ferronickel alloy steel by maintaining technical specifications, can reduce 10.9% and 9.1% of GWP absolute value.

Moreover, due to limited access to precise transportation distances for waste and ore within the mine site, several LCA models were run using primary data and satellite imagery. Varying the maximum and minimum distances for ore, waste, and overburden materials only changed the GWP by −0.24% to +1.32%, reflecting the lower contribution of mining operations to the overall GWP of processed Spodumene concentrate.

Starting in 2023, a new mining fleet will gradually be introduced, consisting of CAT 785 trucks with a 140-tonne capacity and CAT 6020 excavators with a 12 m^3 bucket capacity. Previously, the project used CAT 777 trucks and CAT 6015 excavators with 90-tonne and 8 m^3 capacities, respectively. A new background flow was incorporated into subsequent models based on the updated equipment. The analysis showed that the new fleet, with larger trucks and excavators, resulted in lower impacts (0.34% GWP per functional unit) due to reduced specific fuel consumption during the mining stage.

To compare the grinding technologies in the CGP1 and CGP2 processing plants, an LCA model was developed without the high-pressure grinding rolls (HPGR) in the CGP2 plant, and another model included HPGR for all plants. The findings highlight the importance of technological advancements in the grinding sector. If the CGP2 plant's grinding unit had remained the same as CGP1's, GWP impacts would have been approximately 17.3% higher. Additionally, implementing HPGR in all plants (CGP1 and TGP) could reduce GWP by up to 19.4% for SC6 production.

Finally, an LCA model was constructed using only existing ecoinvent flows and compared to the base case. Utilising Ecoinvent flows for all background processes in mining and processing resulted in lower GWP values (−3.76%) compared to the base case. This discrepancy is primarily due to the absence of drilling blast-hole flows in ecoinvent, the omission of oleic acid (flotation collector) flow—sourced from AusLCI—and the lack of flows for all mining machinery. These differences underscore how impacts can vary when relying solely on one database.

For the water consumption impact category, the final absolute values follow a similar trend to the global warming potential category. However, a notable difference arises in the maximum flotation reagent use (Flotation Max in diagram) scenarios, specifically related to the increased consumption of oleic acid. The results of this sensitivity analysis for both global warming potential and water consumption are summarised in Fig. 4, respectively.

3.4. Benchmarking

3.4.1. Spodumene concentrate

To compare the carbon footprint of the Spodumene concentrate production process in this study with previous research summarised in Table 1, Fig. 5 illustrates the differences between this detailed analysis and earlier studies that utilised approximated and simplified models. As evident from both the table and the analysis of the life cycle inventory (LCI) used in this study, the approximations made from other industries result in significantly different values, which are not appropriate for representing ore or concentrate production. For example, the Spodumene production process flow in the ecoinvent database (Hischier, 2007) lacks almost all consumables required for the processing stage. Additionally, the amount of explosives specified is substantially lower than what is required for actual lithium hard rock mining operations in Australia. Furthermore, aside from chemicals and consumable materials, the database does not include any waste flows for Spodumene mining, and it fails to account for transportation within the mine—a critical operation in mining activities. Similarly, essential processes such as excavation, mining road construction and maintenance, and blast hole drilling are entirely excluded from the Spodumene production flow in this database. Notably, the electricity consumption in this database is underestimated by 284% compared to the primary data used in this study, clearly indicating that key operations like grinding and flotation were omitted from the assessed system. The same shortcomings apply to the Stamp model.

Moreover, Kelly et al. (2021) also failed to account for many essential consumables in both the mine and processing plant, and this incomplete LCI was subsequently adopted by Chordia et al. (2022). Lastly, it is crucial to note that none of these studies provided a clear method for calculating or approximating energy and consumables consumption, in contrast to the rigorous approach taken in this study.

This improved analysis highlights the importance of using high-quality, primary data to ensure the accuracy of life cycle assessments, particularly in the context of critical mineral extraction.

3.4.2. Lithium carbonate and lithium hydroxide monohydrate

In line with the previous section, the values for lithium hydroxide monohydrate and lithium carbonate from prior studies are compared with the outcomes of this study. The results indicate a 36.8% and 30.6% reduction in carbon dioxide equivalent emissions for lithium carbonate

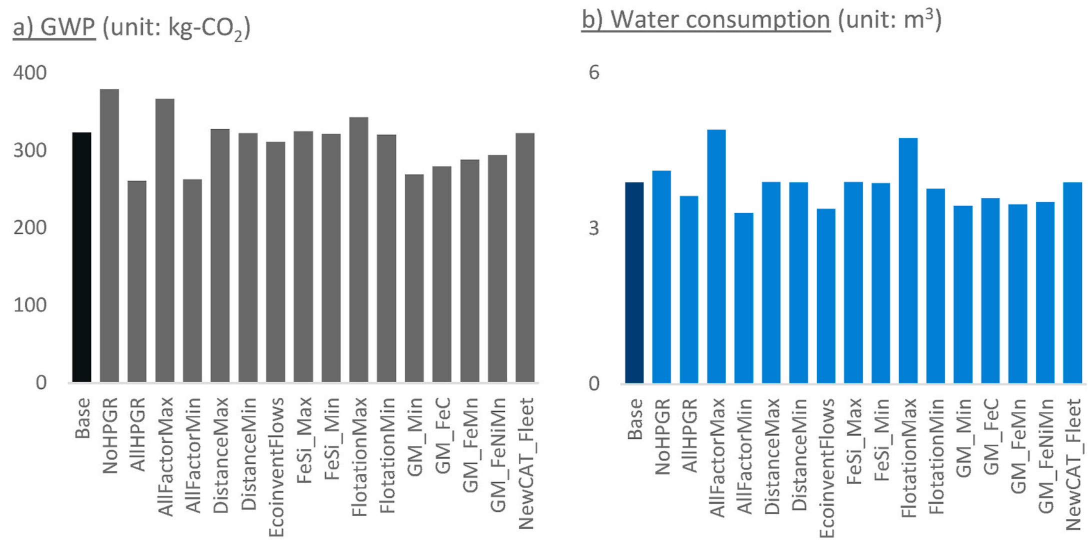

Fig. 4. GWP and Water Consumption Sensitivity Analysis Scenario results.

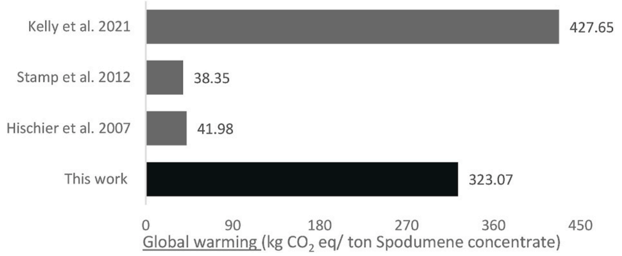

Fig. 5. – Global warming potential comparison of previous studies with this research.

and lithium hydroxide monohydrate production, respectively, when using the Spodumene concentrate modelled in this study in place of Kelly et al. (2021) inventory for lithium compound production.

As illustrated in Fig. 6, differences in study scope, process coverage, data sources, and data quality have led to varying impact assessments. Most of the prior studies exhibit significant data gaps, relying heavily on approximations and oversimplifications. These evident research deficiencies, along with the lack of transparent data collection methods, highlight the relevance and impact of this study. Consequently, this research will play a pivotal role in future decision-making processes and studies in this field.

This refined approach not only addresses the existing data quality issues but also sets a benchmark for more accurate environmental assessments of lithium production, offering a valuable reference for future life cycle assessments.

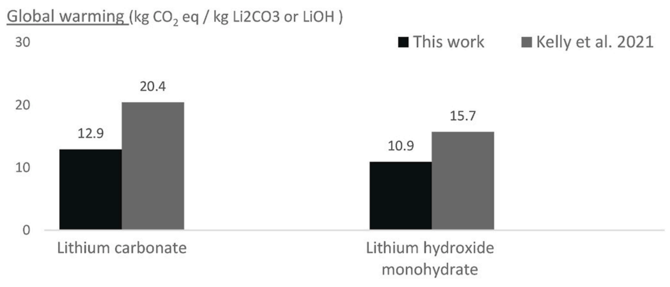

Fig. 6. – Benchmarking GWP category of LiOH and Li_2CO_3 production of Kelly et al., 2021) LCI with this study SC6.

4. Conclusions

In conclusion, given the critical role of lithium mining in the energy transition, this study aimed to develop a comprehensive life cycle inventory (LCI) for the mining and processing of lithium ore (Spodumene). By using primary data, this study significantly improves the accuracy and quality of lithium mining LCA models, which were previously based on approximations from iron ore and lime comminution and manganese processing. This LCI serves as a foundational reference for future LCA modelling in the mining sector. Although developed for the largest Spodumene mine globally, the methodology can be adapted for other Spodumene projects and mineral commodities. The main limitation of this study in the mine modelling sector was the lack of access to historical data for exact travel distances of trucks, which are measured by satellite imagery instead in this study.

The life cycle impact assessment (LCIA) was conducted using the ReCiPe midpoint method, with additional checks across other methods to assess various impact categories and quantify the burdens of each input-output flow in the mine and processing plant. This study uniquely combined primary data with satellite imagery, a first for lithium mining projects. Beyond the comprehensive LCI development, the paper also provides valuable benchmarking for lithium hydroxide monohydrate, lithium carbonate, and Spodumene concentrate production, highlighting how access to higher-quality data can significantly enhance LCA modelling outcomes.

This study focused on operations during the year 2022, but the methodology can be extended to future years of the project. Additionally, the constructed mining and processing flows provide a solid foundation for future research efforts, as databases like ecoinvent and Gabi lack many of these essential flows. With this comprehensive approach, other raw materials, including critical minerals, can be accurately modelled, enabling policymakers and stakeholders to make informed decisions with full transparency. This supports the practice of responsible mining and sourcing, contributing to more sustainable resource management. Finally, for other commodities mined via open-pit methods, the detailed input and output flow modelling from this study can be replicated using the provided formulas adjusted for project-specific conditions. For processing, relying on first-hand data is strongly advised to avoid estimation errors.

CRediT authorship contribution statement

Shayan Khakmardan: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Robert H. Crawford:** Writing – review & editing, Supervision. **Damien Giurco:** Writing – review & editing, Resources, Funding acquisition. **Wen Li:** Writing – review & editing, Supervision, Software, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wen Li reports financial support was provided by Future Battery Industries Cooperative Research Centre. If there are other authors, they 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145123.

Data availability

Data will be made available on request.

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