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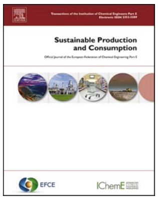

Understanding the effects of mining and processing parameters on Life Cycle Assessment of Greenbushes Spodumene production

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ABSTRACT

The rapid transition to clean energy has intensified demand for lithium, a critical element for battery production, yet lithium extraction imposes substantial environmental burdens. While the Life Cycle Assessment (LCA) provides a snapshot of environmental impacts, it does not account for dynamic changes in mining and processing operations, such as declining ore grade. This study conducts comprehensive LCAs of Spodumene ore and concentrate production from 2009 to 2023 at the Greenbushes project, empirically analysing how variable parameters influence environmental impacts. Regression analysis identifies the waste-to-ore ratio as the most significant factor affecting most of the mining-related impacts, while ore grade and yield play a dominant role in processing operations for most of the impact categories. Consequently, the global warming potential of producing Spodumene concentrate increased by almost 42.7 % between 2011 and 2023. Moreover, electricity and grinding media consistently contributed the most to the carbon footprint throughout the study period, though their combined share declined from 81.1 % to 57.1 %, whereas diesel consumption rose from 3 % to nearly 20.1 %, mainly due to site expansion.

1. Introduction

The clean energy transition moves away from fossil-based energy and utilises significant quantities of minerals and metals for the production and storage of energy from renewable technologies and batteries (IEA, 2024, Kosmol et al., 2018). Lithium is currently a dominant metal used in battery technologies for electric vehicles and stationary energy storage (Khakmardan et al., 2024a, 2023a, 2023b). Conventionally, lithium is extracted from continental brines and hard rock deposits (Mohr et al., 2012). Additionally, existing lithium production projects have expanded by lowering their cut-off grades, thereby increasing production capacities and the scale of deposits in conjunction with more complicated processing technologies to meet the increasing demand (Werner et al., 2020; Zhao et al., 2021). The increasing trend of mineral resource extraction has raised environmental concerns worldwide (Hofmann et al., 2018, Khakmardan et al., 2023a, 2023b, Alessia et al., 2021).

Life Cycle Assessment (LCA) is widely utilised to address the environmental performance of these activities and associated technologies (Hollberg and Ruth, 2016; Kara and Hauschild, 2024; Hauschild et al., 2018). However, LCA outcomes are highly dependent on data quality. The current available data for Spodumene production, in this regard, are static, approximated values of iron ore mining and lime comminution. This leads to just having a low-quality snapshot analysis of the Spodumene mining and processing activities (Cooper and Kahn, 2012; Rolinck et al., 2023). These approximations are based on studies conducted in 2007 and 2012 by Hischier et al. and Stamp et al., respectively (Frischknecht et al., 2007; Stamp et al., 2012). Consequently, many subsequent assessments, including those by Manjong et al. (2021) and Ambrose and Kendall (2020), rely on outdated data, limiting their effectiveness in informing decision-making due to data quality constraints (Manjong et al., 2021; Ambrose and Kendall, 2020). Additionally, these assessments lack relevance to real-world Spodumene mining and extraction conditions and are typically unsupported by model-based simulations, leaving crucial parameter relationships unverified (Kelly et al., 2021; Grant et al., 2020; Chordia et al., 2022; Jiang et al., 2020). Our recent work further highlights that nearly all LCA models and studies on lithium extraction contain significant data gaps across extraction stages, resulting in incomplete life cycle inventories (Rolinck et al., 2023). Therefore, there is a need to quantify and fill the data gaps

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while capturing the dynamic nature of extracting lithium from mineral resources.

To address the existing limitations, this paper focuses on constructing a dynamic LCA for the period 2009–2023, using high-quality primary data from the world's largest Spodumene concentrate plant located in Greenbushes, Western Australia. Variable parameters within the mining and processing stages are identified and screened through an empirical approach, as outlined in Section 2. Section 3 presents the LCA results along with statistical analyses used to identify and validate the most influential parameters for each mining and processing operation. Finally, Section 4 concludes the study and provides recommendations for future research. This work provides valuable insights into the key drivers of environmental impacts in Spodumene concentrate production.

2. Method

A dynamic and parametric LCA study was conducted in accordance with ISO 14040 standards, encompassing its four primary phases: goal and scope definition, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and interpretation, covering the study years 2009–2023 (Standardization, 2006). OpenLCA software was utilised for this purpose.

2.1. LCA goal and scope

The primary objective of this dynamic LCA study was to identify and quantify the environmental burdens associated with producing 1 t of each Spodumene ore (ROM), and Spodumene concentrate with 6 % lithium oxide (Li_2O) content (SC6) over the period 2009–2023, using primary data. The analysis encompasses all mining and processing operations, including infrastructure development, direct land disturbance, site preparation and overburdening, drilling and blasting, loading and hauling, equipment maintenance, sequential comminution, separation and classification techniques, dewatering, reagent preparation, and tailings management. The study's scope extends from mine to scale (cradle-to-gate). Fig. 1 illustrates the system boundaries defined for this dynamic LCA.

2.2. Life cycle inventory

The LCI analysis was conducted using a comprehensive approach that combined previous studies by the author, on-site visits, interviews, and publicly available technical reports from the project spanning 2009–2023, including EPA, ASX, NI43–101, and SK-1300 reports, as well as the ecoinvent and AusLCI databases for the background (SRKConsulting, 2024, SRKConsulting, 2023, SRKConsulting, 2022, Greig et al., 2022, Greig et al., 2018, Ingham et al., 2012, Ingham et al., 2011, Ingham et al., 2010, Ingham et al., 2009, MDO Data Online Inc., 2023, Talison, 2023, Talison, 2022, Glass, 2022, Callegari et al., 2018, Khakmardan et al., 2025). Additionally, project and field assessments were supplemented with satellite imagery to evaluate land disturbance and infrastructure at the mine and processing sites, as shown in Fig. 2. It is important to note that images from 2009 to 2011 were approximated using the earliest available satellite images from March to August 2012 (Khakmardan et al., 2024b, 2025).

The input flows for this analysis include various energy carriers (electricity, diesel, LPG), all resources and materials used in operations (such as maintenance chemicals, explosives, drilling rods and bits, water and pulp transfer pipes, dense media, flotation chemical reagents, flocculants, and lubricants), mining and processing infrastructure, water, and elementary flows associated with land occupation and land-use transformation. The primary output flows are the mineral product and waste generated during mining, and the Spodumene concentrate and tailings from the processing stage. Also, emissions, by-products, and other types of waste are considered. Table 1 presents the ranges of all input and output flows of the Spodumene concentrate production over the study period (Detailed inputs and outputs for Spodumene ore and concentrate production for each year are listed in the Supplementary Excel file SI-1).

2.3. Screening the parameters

Key design and operational parameters were identified by referencing widely recognised mining and processing handbooks and through consultations with experts in each field. For open-pit mining, the critical parameters include deposit type, mining method, cut-off grade, waste-to-ore ratio, operation depth, distance from the exploitation site to the waste dump and ore stockpile, bench height, slope and final pit slope, road width and slope, alluvial depth, groundwater

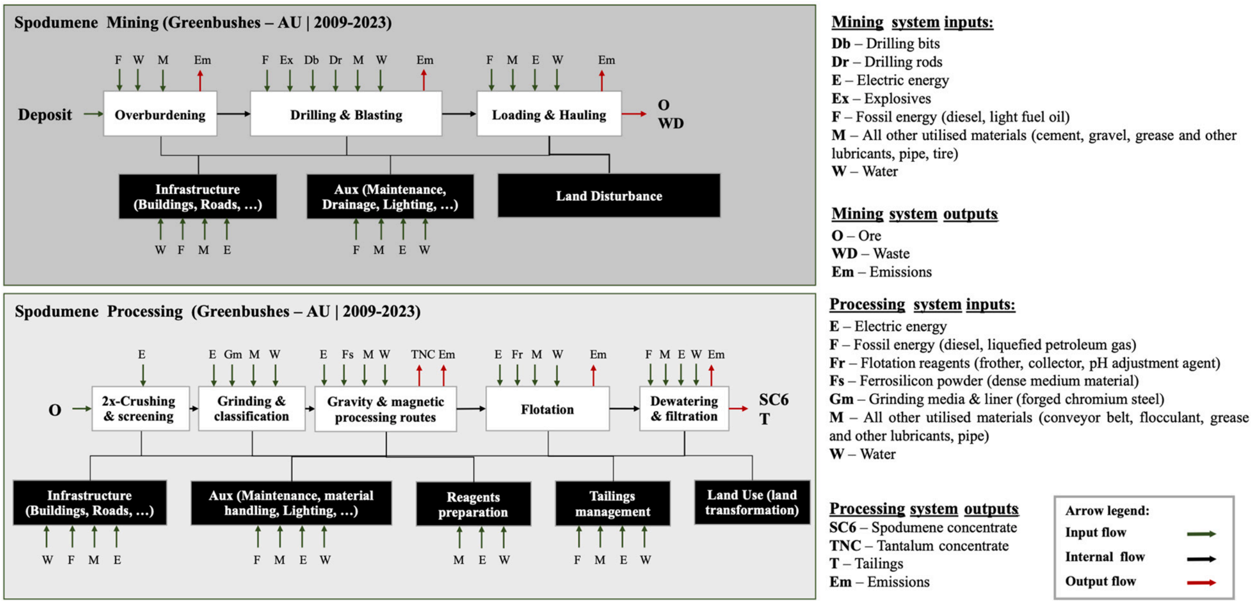

Fig. 1. Mining and processing system boundary.

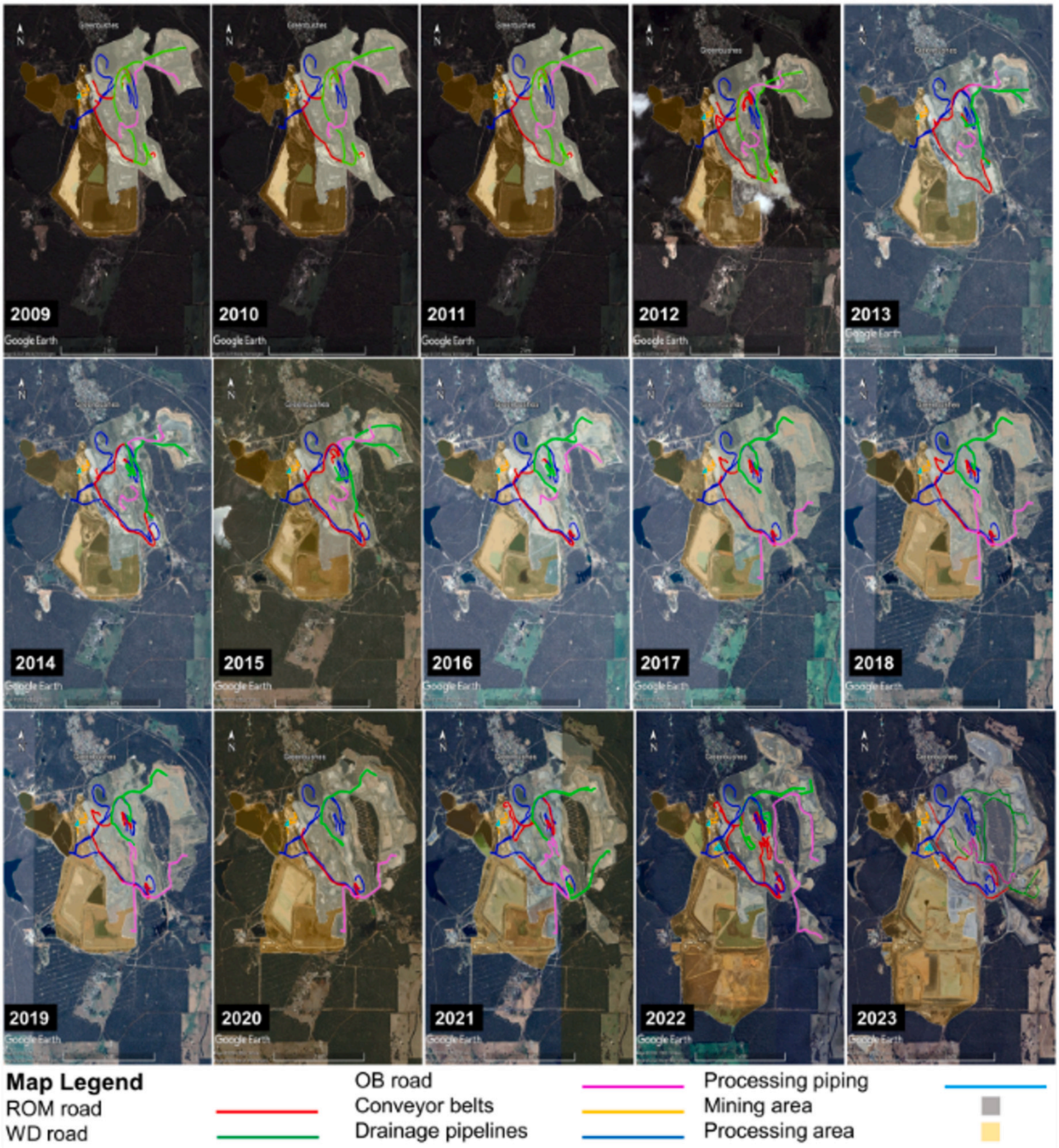

Fig. 2. Satellite imagery of Greenbushes mining and processing area, 2009–2023.

ingress, mining block dilution factor, ore recovery, blast hole diameter and length, burden, spacing and blasting hole patterns, as well as machinery performance (Darling, 2011; Hustrulid et al., 2013).

Similarly, for processing operations, the primary parameter is the processing method and flowsheet design, which depends on the specific characteristics that distinguish valuable minerals in the ore (Spodumene in this case study) from gangue minerals (like biotite, muscovite, tourmaline, quartz and feldspar in this case), such as differences in specific gravity, colour, magnetic and electric susceptibility, shape, and hydrophobicity (Weiss, 1985; Wills and Finch, 2015). Additional parameters include plant throughput, capacity and equipment mechanism, ore and concentrate grade, recovery, yield, concentration ratio, liberation size of valuable minerals, operational solid-to-liquid ratio, reagents type and consumption rate, and equipment performance.

The Greenbushes mine in Australia is the world's largest Spodumene operation, contributing almost 42 % and 60 % of global and Australian Spodumene production annually (Jaskula, 2024, 2018, 2015, 2011, 2007). It employs open-pit mining for ore extraction, followed by comminution to liberate Spodumene from gangue minerals. Subsequent physical separation and flotation processes yield a Spodumene concentrate with almost 75 % Spodumene content, equivalent to 6 % Li_2O, commonly called SC6. For the Greenbushes mine and processing plant, the constant and variable parameters over the years of operation are summarised in Tables 2 and 3, respectively. These parameters and data were compiled from multiple sources, including technical and financial reports covering the period from 2009 to 2023, as well as direct site visits and interviews with engineers working at the mine and processing plant for validation purposes (SRKConsulting, 2024, SRKConsulting, 2023, SRKConsulting, 2022, Greig et al., 2022, Greig et al., 2018, Ingham et al., 2012, Ingham et al., 2011, Ingham et al., 2010, Ingham et al., 2009, MDO Data Online Inc., 2023, Talison, 2023, Talison, 2022, Glass, 2022, A. Callegari et al., 2018).

Table 1
Range of input and output flows of Spodumene concentrate production within 2009–2023.

	Min	Q1	Median	Q3	Max	Unit
System inputs						
Mineral resources						
Basalt	2.69E+00	5.78E+00	6.65E+00	8.97E+00	1.29E+01	t
Spodumene	1.92E+00	2.44E+00	2.88E+00	3.28E+00	4.11E+00	t
Tantalum, in ground	8.06E−01	1.02E+00	1.21E+00	1.38E+00	1.73E+00	kg
Materials and chemicals						
Blasting (explosives)	1.57E+00	3.04E+00	3.27E+00	4.10E+00	5.28E+00	kg
Oleic acid	1.14E+00	1.27E+00	1.44E+00	1.58E+00	2.20E+00	kg
Propylene glycol	1.14E−01	1.27E−01	1.44E−01	1.58E−01	2.20E−01	kg
Soda ash	5.01E−01	6.08E−01	7.38E−01	8.57E−01	1.22E+00	kg
Sodium hydroxide	1.06E+01	1.06E+01	1.06E+01	1.06E+01	1.90E+01	kg
Polyacrylamide	1.36E−01	1.53E−01	1.73E−01	1.90E−01	2.45E−01	kg
Grinding media	1.05E+01	1.18E+01	1.33E+01	1.43E+01	1.56E+01	kg
Dense media	2.70E−01	3.03E−01	3.42E−01	3.77E−01	4.84E−01	kg
Grinding media manufacturing	1.05E+01	1.18E+01	1.33E+01	1.43E+01	1.56E+01	kg
Conveyor belt	2.00E−04	2.00E−04	2.00E−04	2.00E−04	3.91E−04	m
PE pipe	1.10E−03	1.66E−03	2.41E−03	3.06E−03	5.46E−03	m
Water consumption						
Water (decarbonised)	4.33E−01	8.55E−01	1.29E+00	1.59E+00	2.80E+00	kg
Tap water	4.38E+00	8.05E+00	1.03E+01	1.56E+01	3.93E+01	kg
Water (harvested from rainwater)	2.42E+03	2.92E+03	3.08E+03	3.30E+03	4.94E+03	kg
Energy consumption						
Electricity, medium voltage	9.12E+01	1.09E+02	1.18E+02	1.40E+02	1.83E+02	MJ
Gas and oil consumption						
Diesel	1.00E+02	1.83E+02	2.35E+02	3.44E+02	7.24E+02	MJ
Liquified petroleum gas	1.02E+00	1.85E+00	2.31E+00	3.10E+00	4.26E+00	MJ
Mining activities						
Transport by mining truck	2.02E+01	4.76E+01	5.22E+01	6.47E+01	1.10E+02	t*km
Blasthole drilling	1.54E−01	1.99E−01	2.32E−01	2.66E−01	3.27E−01	m
Excavation by mining excavator	1.72E+00	3.31E+00	3.56E+00	4.35E+00	5.57E+00	m^3
Land use						
Occupation, mineral extraction site	4.07E+00	6.60E+00	8.70E+00	1.06E+01	1.85E+01	m^2*a
Transformation from forest	2.33E−02	1.93E−01	2.70E−01	3.81E−01	6.37E−01	m^2
Transformation to mineral extraction site	2.33E−02	1.93E−01	2.70E−01	3.81E−01	6.37E−01	m^2
Occupation, industrial area	4.87E+00	5.70E+00	8.34E+00	9.77E+00	1.74E+01	m^2*a
Transformation from forest	6.40E−02	2.75E−01	3.84E−01	5.67E−01	9.49E−01	m^2
Transformation to an industrial area	6.40E−02	2.75E−01	3.84E−01	5.67E−01	9.49E−01	m^2
Equipment and infrastructure						
Building (hall)	4.98E−04	5.24E−04	6.12E−04	9.58E−04	1.52E−03	m^2
Building (multi-storey)	9.44E−03	9.77E−03	1.07E−02	1.63E−02	2.66E−02	m^3
Mining road construction	1.27E−02	2.08E−02	2.85E−02	4.44E−02	8.10E−02	m*a
Mining road maintenance	1.27E−02	2.08E−02	2.85E−02	4.44E−02	8.10E−02	m*a
System outputs						
Product						
Spodumene concentrate	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	t
By-product						
Tantalum concentrate	4.18E−01	4.18E−01	4.18E−01	4.18E−01	4.18E−01	kg
Wastes						
Tailings	9.20E−01	1.44E+00	1.88E+00	2.28E+00	3.11E+00	t
Waste rock	2.69E+00	5.78E+00	6.65E+00	8.97E+00	1.29E+01	t
Tantalum, in-ground	4.18E−01	4.18E−01	4.18E−01	4.18E−01	4.18E−01	kg
Scrap steel	6.28E−02	1.15E−01	1.48E−01	2.24E−01	4.58E−01	kg
Waste electric and electronic equipment	1.15E−02	2.12E−02	2.72E−02	4.10E−02	8.90E−02	kg
Emissions to air						
Carbon monoxide	3.51E+01	6.46E+01	8.29E+01	1.25E+02	2.64E+02	g
Nitrogen oxides	6.42E+01	1.18E+02	1.52E+02	2.29E+02	5.08E+02	g
Particulates, <2.5 μm	4.25E+00	7.82E+00	1.00E+01	1.51E+01	3.42E+01	g
Particulates, >10 μm	1.31E+02	2.41E+02	3.10E+02	4.67E+02	1.01E+03	g
Sulphur dioxide	4.58E−02	8.43E−02	1.08E−01	1.63E−01	3.66E−01	g
VOC, volatile organic compounds	4.68E+00	8.62E+00	1.11E+01	1.67E+01	3.70E+01	g
Water (gas)	6.13E−01	1.25E+00	1.88E+00	2.43E+00	4.46E+00	m^3
Emissions to water						
Water (liquid)	4.73E+02	8.68E+02	1.12E+03	1.68E+03	2.15E+03	kg

2.4. Life cycle impact assessment and parameterisation

The ReCiPe Midpoint (H) 2016 method was selected for impact assessment (Huijbregts et al., 2016), and discussed comprehensively in Section 3 along with the interpretation of the models outcome.

After characterising the empirical observations of Greenbushes environmental impacts, stepwise regression analysis was utilised to identify the significant parameters influencing Spodumene mining and processing. The backward elimination method was employed, where all variable parameters were initially included in the model. At each step, the parameter with the highest *p*-value was removed, and this iterative process continued until only statistically significant parameters (p-value <0.05) remained (Chatterjee and Hadi, 2015; Sen and Srivastava, 2012).

Table 2
Mining parameters (2009–2023).

Mining parameters	Type	Range	Source
Deposit type	Constant	LCT-pegmatite	Technical report (Greig et al., 2022)
Mining method	Constant	Open pit	Technical report (Greig et al., 2022)
Mining machinery	Constant	CAT 777 truck, CAT 6015 excavator, D9 dozer, CAT 777 water truck, M16 grader, D65 Epiroc drill	Technical report (Greig et al., 2018)
Cut-of-grade	Variable	0.7 to 4.0 % Li_2O	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Ore grade	Variable	2.1 to 4.1 % Li_2O	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Waste-to-ore ratio	Variable	1.4 to 5.3	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Depth	Variable	0-95 m for C1 pit, 0-230 m for C3 pit, 0-300 m for Kapanga	Technical reports (Greig et al., 2022, 2018)
Distance (ore)	Variable	2.26 to 3.82 km	Google Earth satellite imagery 2012–2024
Distance (waste)	Variable	2.05 to 3.77 km	Google Earth satellite imagery 2012–2024
Distance (overall)	Variable	4.3 to 7.6 km	Google Earth satellite imagery 2012–2024
Bench height	Constant	5 m for ore blocks, 10 m for waste blocks	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Final bench height	Constant	30 m	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Final pit slope	Constant	50°	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Road slope	Constant	6° or 1:10	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Road width	Constant	24 m till 2018, 26 m till 2022, 33 m from 2022	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Alluvial depth	Constant	36 cm	Technical report (Ingham et al., 2011)
Groundwater ingress	Constant	25 L/s	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Mining block dilution factor	Constant	5 % for the period (2013-2020), the rest assumed to be 0 %	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Ore block recovery	Constant	100 %	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Blast hole depth	Constant	5.86 m for ore blast holes, 10.95 m for waste blast holes	Calculation (Hustrulid et al., 2013)
Blast hole diameter	Constant	115 mm for ore blast holes, 127 mm for waste blast holes	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Blasting hole patterns	Constant	2.3 m × 2.7 m for ore blocks, 4.1 m × 4.8 m for waste blocks	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Spacing	Constant	3.3 m for ore blocks, 3.7 m for waste blocks	Calculation (Hustrulid et al., 2013)
Burden	Constant	2.9 m for ore blocks, 3.2 m for waste blocks	Calculation (Hustrulid et al., 2013)

For mining and processing operations, 15 observations spanning the years 2009–2023 were analysed. However, for processing operations, the seven most recent observations (2017–2023), which provided higher-quality data on electricity usage, were prioritised for stepwise regression analysis. To validate the models, the same method was applied to different subsets of data, ensuring reliability, consistency of observed patterns, and robustness in identifying the most influential parameters across both datasets. The statistical analyses were conducted using the Data Analysis Tool in Microsoft Excel and Minitab 22.1.

3. Results and discussion

3.1. Life cycle impact assessment analysis

The dynamic LCIA results across all impact categories are summarised in Table 4. Most impact categories have at least doubled comparing the minimal and maximum values over the study period, highlighting the need for this dynamic approach. The detailed year-to-year LCIA results for Spodumene ore (ROM) and Spodumene concentrate (SC6) production are provided in the Supplementary Excel file 2 (SI-2). Furthermore, Figs. 3 and 4, as heat maps, illustrate the trend of changes in each impact category for mining and processing operations, respectively.

From 2009 to 2023, the environmental intensity of producing one tonne of Spodumene ore varied greatly (see SI-2, ROM sheet). As can be seen from most of the indicators in Fig. 3, mining operations in 2010 had the worst environmental performance, followed by the year 2011. Over time, there is a noticeable shift toward lower impact levels until 2020, but they have worsened again in recent years. The main reason for this trend is the mine expansion for increasing production, as evident in the satellite image shown in Fig. 2. Expansion phases in 2010–11 and 2022–23 more than doubled most impact indicators. Specifically, Chemical Grade Plant 1 (CGP1) was constructed in 2010 and commissioned in 2011 to process larger volumes of lower-grade ore, while CGP2 was similarly constructed and commissioned in 2021, for processing of more diluted ores with waste rocks. The footprint peaked in 2010, when developing the C1 and C3 pits generated 3.8 times more mineral waste than in 2016. By contrast, 2016 recorded the lowest impacts because accessible ore blocks, selective mining, shortened haul distances to both the waste dump and the ore stockpile and reduced the waste-to-ore ratio in this year. Due to a higher waste-to-ore ratio, the haulage equivalent and explosives needed per tonne of ore in 2010 were more than three times that of 2016 and nearly twice that of all other mining years, except for 2011, 2015 and 2023 (see SI-1, ROM sheet).

Notably, direct land occupation and land transformation of mining

Table 3
Processing parameters (2009–2023).

Processing parameters	Type	Range	Source
Processing method	Constant	Crushing, screening, dense-medium separation, magnetic separation, classification, grinding, flotation, dewatering	Technical reports (Greig et al., 2022, 2018, Ingham et al., 2012, 2011, 2010, 2009, Glass, 2022)
Plant design capacity (input ore)	Constant	350ktpa TGP, 2Mtpa CGP1, 2.4Mtpa CGP2	Technical reports (SRKConsulting, 2023, 2022)
Plant design feed grade (% Li_2O)	Constant	3.8 % TGP, 2.7 % CGP1, 1.7 % CGP2	Technical reports (SRKConsulting, 2023, 2022)
Recovery (overall)	Variable	55.95 to 88.4 %	Calculation (Weiss, 1985, Wills and Finch, 2015)
Concentration ratio (overall)	Variable	1.92 to 4.11	Calculation (Weiss, 1985, Wills and Finch, 2015)
Yield (overall)	Variable	24.35 to 43.96 %	Calculation (Weiss, 1985, Wills and Finch, 2015)
Ore grade (TGP)	Variable	3.72 to 4.10 % Li_2O	Technical reports (SRKConsulting, 2023, 2022)
Ore grade (CGP1)	Variable	2.46 to 2.71 % Li_2O	Technical reports (SRKConsulting, 2023, 2022)
Ore grade (CGP2)	Variable	1.96 to 2.18 % Li_2O	Technical reports (SRKConsulting, 2023, 2022)
Ore grade (overall)	Variable	2.10 to 4.10 % Li_2O	Technical reports (SRKConsulting, 2023, 2022)
Product grade range (each plant individually)	Variable	5.88 to 6.94 % Li_2O	Technical reports (SRKConsulting, 2023, 2022)
Product grade (average overall)	Variable	6.03 to 6.25 % Li_2O	Technical reports (SRKConsulting, 2023, 2022)
Liberation size	Constant	~3 mm for gravity separation, ~150 µm for grinding, ~75 µm for regrinding	Interview with the expert during the site visit
Spodumene specific gravity (t/m3)	Constant	3.1	Technical report (Ingham et al., 2011)
Gangue's specific gravity (t/m3)	Constant	2.65 for quartz, 2.7 for muscovite & biotite, 2.6 for feldspar	Technical report (Ingham et al., 2011)
Spodumene magnetic susceptibility	Constant	Negligible (diamagnetic)	Reference handbook (Garrett, 2004)
Gangue's magnetic susceptibility	Constant	Tourmaline, muscovite and biotite are weakly paramagnetic (paramagnetic)	Reference handbook (Garrett, 2004)
Solid-to-liquid ratio	Constant	Per each sub-operation	Interview with the expert during site visit
Grinding media type & consumption rate	Constant	Steel balls with different diameters at a rate of 0.3 % ore	Interview with the expert during site visit
Dense-media reagent type & consumption rate	Constant	120 g per tonne of ore FeSi 270	Interview with the expert during site visit
Flotation reagent I type & consumption rate	Constant	500 g per tonne of ore of oleic acid (as the collector)	Interview with the expert during site visit
Flotation reagent II type & consumption rate	Constant	50 g per tonne of ore of polypropylene glycol (as frother)	Interview with the expert during site visit
Dewatering reagent type & consumption rate	Constant	60 g per tonne of ore of flocculant	Interview with the expert during site visit

CGP = chemical grade plant.
TGP = technical grade plant.

operations have an overall declining trend among all study years. As mining progressed deeper rather than widening the pit, the land-disturbance footprint fell, and by 2023, the land-disturbance footprint was 4.7 times lower than in 2010.

As shown in Fig. 4, the SC6 production demonstrates a rising trend in environmental impacts, particularly in the latter years of the study (see SI-2, SC6 sheet). Environmental performance deteriorated markedly in 2020–2023, when 14 of 18 life-cycle impact indicators reached their maximum values. The primary driver is a continuous decline in ore grade, which lowers processing yield and forces higher specific inputs of energy, grinding media and reagents (see SI-1, SC6 sheet).

Diesel consumption intensity rose steeply during the study period. Relative to the 2016 benchmark, it was 17 % higher in 2020, 107 % higher in 2022 and 208 % higher in 2023; against the 2011 baseline, these increases were 70 %, 199 % and 345 %, culminating in a more than seven-fold surge over the full 2009–2023 interval. Electricity demand followed the increasing trend with less intensity compared to diesel, exceeding the 2016 level by 74 % (2020), 22 % (2022) and 5 % (1). Reagent consumption mirrored these trends. Flotation reagents consumption was 25 % higher in 2023 than in 2016, and 70 % higher than in 2011, while grinding-media consumption rose by 3 % (1) and 10 % (2022) above 2016, or up to 40 % above the 2011 reference year.

Collectively, these escalations explain the bad environmental performance in 2020–2023, whereas 2011 and 2016 stand out as the best-performing years owing to higher Li_2O grades and coarser liberation sizes that reduced processing intensity.

3.2. *Hotspot analysis*

Fig. 5 summarises the dynamic hotspot analysis for Spodumene ore production between 2009 and 2023 to explore the contribution of each service in this mining activity for selected impact categories with different trends. Across all assessed impact categories, drilling and blasting operations remain the principal contributor because explosives manufacture remains both energy and material-intensive in the upstream inventory. In addition, the blasting phase releases considerable volumes of noxious gases (e.g., NO_x and CO), further amplifying the environmental burden of blasting. Haulage is generally the second largest source of impacts, driven by the substantial diesel demand and long operating hours of the truck fleet.

Freshwater eutrophication is the notable exception; here, auxiliary activities such as road construction and maintenance rank second. Their influence has declined over time because electricity used to crush and grade road base is amortised over a steadily rising ore throughput.

Land use occupation displays a trajectory unlike any of the other 17 impact categories examined. The burden fell nearly sixfold, from 6.1 m^2·a in 2009 to 1.1 m^2·a in 2023, largely because lateral growth ceased after the major expansions of pits C1 and C3 (2009–2011), and extraction subsequently shifted to deeper benches within the established footprint. Hotspot analysis corroborates this pattern; Direct land occupation remained the principal driver, but its share declined from 91 % in 2009 to 71 % in 2023 as throughput rose. Auxiliary services linked to

Fig. 3. Heatmap of the dynamic LCIA of Spodumene mining operation.

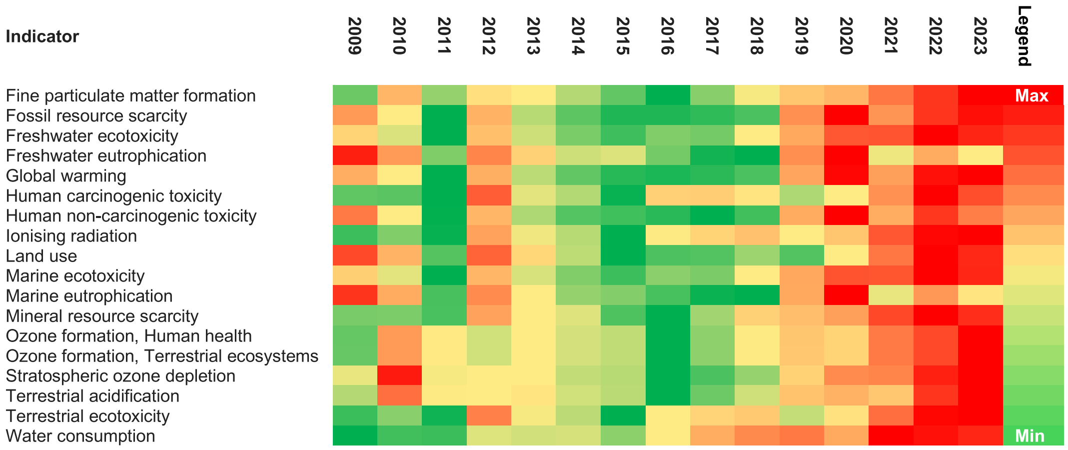

Fig. 4. Heatmap of the dynamic LCIA of Spodumene concentrate production.

Table 4

LCIA range of Spodumene ore and concentrate production between 2009 and 2023.

Indicator	Spodumene mining product ROM			Spodumene processing product SC6			Unit
	Min	Median	Max	Min	Median	Max	
Fine particulate matter formation	0.06064	0.09261	0.15429	0.59355	0.72301	1.05394	kg PM2.5 eq
Fossil resource scarcity	1.64942	2.36831	3.87723	58.57430	69.17450	84.28080	kg oil eq
Freshwater ecotoxicity	0.43112	0.72797	0.80742	14.81410	17.59090	24.05050	kg 1,4-DCB eq
Freshwater eutrophication	0.00165	0.00221	0.00383	0.18971	0.23159	0.33944	kg P eq
Global warming	7.96153	12.14930	19.59060	228.78900	274.34500	326.42100	kg CO$_2$ eq
Human carcinogenic toxicity	0.93666	1.29688	2.12656	120.69000	152.98200	178.04900	kg 1,4-DCB eq
Human non-carcinogenic toxicity	5.66521	9.13187	11.68410	237.00100	288.60600	360.42100	kg 1,4-DCB eq
Ionising radiation	0.12889	0.19926	0.30259	4.46524	5.38825	6.92295	kBq Co-60 eq
Land use	0.99904	1.07637	6.12450	38.87740	45.95530	57.36060	m^{2}a crop eq
Marine ecotoxicity	0.56491	0.95460	1.07967	20.10300	23.73420	32.19930	kg 1,4-DCB eq
Marine eutrophication	0.00029	0.00041	0.00071	0.01428	0.01763	0.02338	kg N eq
Mineral resource scarcity	22.25960	22.28510	22.31010	27.65180	48.58270	77.34890	kg Cu eq
Ozone formation, human health	0.32540	0.49918	0.83971	1.51311	2.23230	3.77538	kg NO$_x$ eq
Ozone formation, terrestrial ecosystems	0.33156	0.50866	0.85579	1.53495	2.26801	3.83158	kg NO$_x$ eq
Stratospheric ozone depletion	0.00004	0.00006	0.00010	0.00021	0.00031	0.00040	kg CFC11 eq
Terrestrial acidification	0.22456	0.34631	0.58251	1.28932	1.80609	2.63996	kg SO$_2$ eq
Terrestrial ecotoxicity	27.96150	61.79000	79.84940	1151.69000	1413.88000	1733.13000	kg 1,4-DCB eq
Water consumption	0.04795	0.07173	0.11837	1.92976	2.59676	3.97331	m^3 eq

ROM: 1 t of mined Spodumene ore.
SC6: 1 t of Spodumene concentrate with 6 % Li$_2$O content.

haul and waste dump road construction and maintenance followed the same downward trend (6 % to 4 %). By contrast, the contribution of drilling and blasting operations climbed from 2 % to 14 %. All remaining flows together do not exceed 4 % on average.

Equipment upgrades in 2023 further reshaped the impact profile. Replacing CAT 6015 with higher-capacity, more fuel-efficient CAT 6020

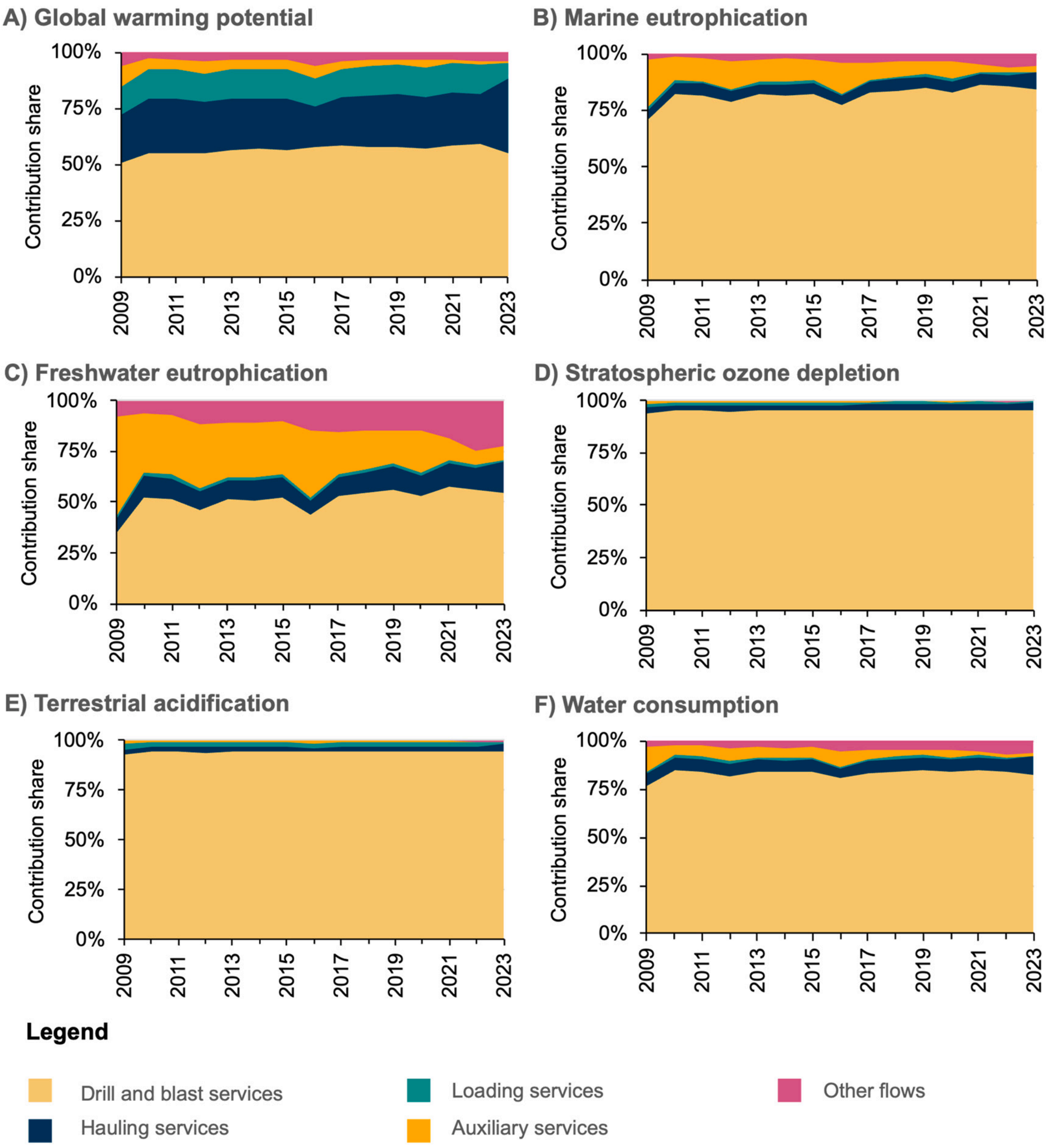

Fig. 5. Dynamic hotspot analysis of Spodumene ore production in Greenbushes for selected impact categories.

excavators lowered the loading contribution in almost every impact category. Conversely, substituting the CAT 777 haul trucks with larger CAT 785 models boosted carrying capacity but left diesel intensity largely unchanged, so the overall haulage impact did not fall.

Fig. 6 summarises the dynamic hotspot analysis for Spodumene concentrate production between 2009 and 2023 for selected impact categories with different trends. Global warming potential (GWP) fell from 288 kg CO_2 eq per tonne of SC6 in 2009 to a study minimum of 228 kg CO_2 eq in 2011, then rose, with minor oscillations, to 326 kg CO_2 eq in 2023. Electricity is consistently the dominant driver, although its share shrank from above 60 % share in 2009 to around 33 % in 2023 as efficiency gains offset rising absolute demand. Grinding media rank second, reflecting progressive ore complexity and finer liberation size; their contribution climbed from around 20 % in 2009 to 32 % in 2016 before easing to 23 % in 2023. On average, Spodumene ore mining contributes 12 % of the total GWP impact, while diesel use associated with beneficiation plant expansions adds 9 %. All other flows combined account for less than 8 %.

Freshwater eutrophication (FEP) and marine eutrophication (MEP) indicators followed a similar trend. The worst years are 2020 (0.34 kg P eq for FEP/0.023 kg N eq for MEP) and 2009 (0.33 kg P eq for FEP/ 0.022 kg N eq for MEP), exceeding 2018 (the best year – 0.19 kg P eq/ 0.014 kg N eq for MEP) by 79 % and 72 % (FEP) and by 64 % and 55 % (MEP), respectively. Electricity again dominates, accounting for 79 to 90 % of FEP and 63 to 81 % of MEP, followed by grinding media consumption and mined ore, during the study period.

Stratospheric-ozone depletion potential (ODP) and terrestrial acidification follow parallel trajectories and share nearly identical source profiles. For ODP, Spodumene ore mining dominates (almost 50 % of the burden on average), with electricity generation contributing 31 %, grinding media 8 %, and both flotation reagents and diesel 5 % each on average; all remaining inputs together account for less than 2 %. Within the Spodumene mining stage, drilling and blasting services are responsible for more than 92 % of the ODP load. Terrestrial acidification mirrors this hierarchy. Its lowest value occurred in 2016 (1.29 kg SO_2 eq), whereas 2022 and 2023 recorded the highest burdens (2.45 kg and 2.64 kg SO_2 eq, respectively), reflecting the additional energy and explosives consumed during recent capacity expansions.

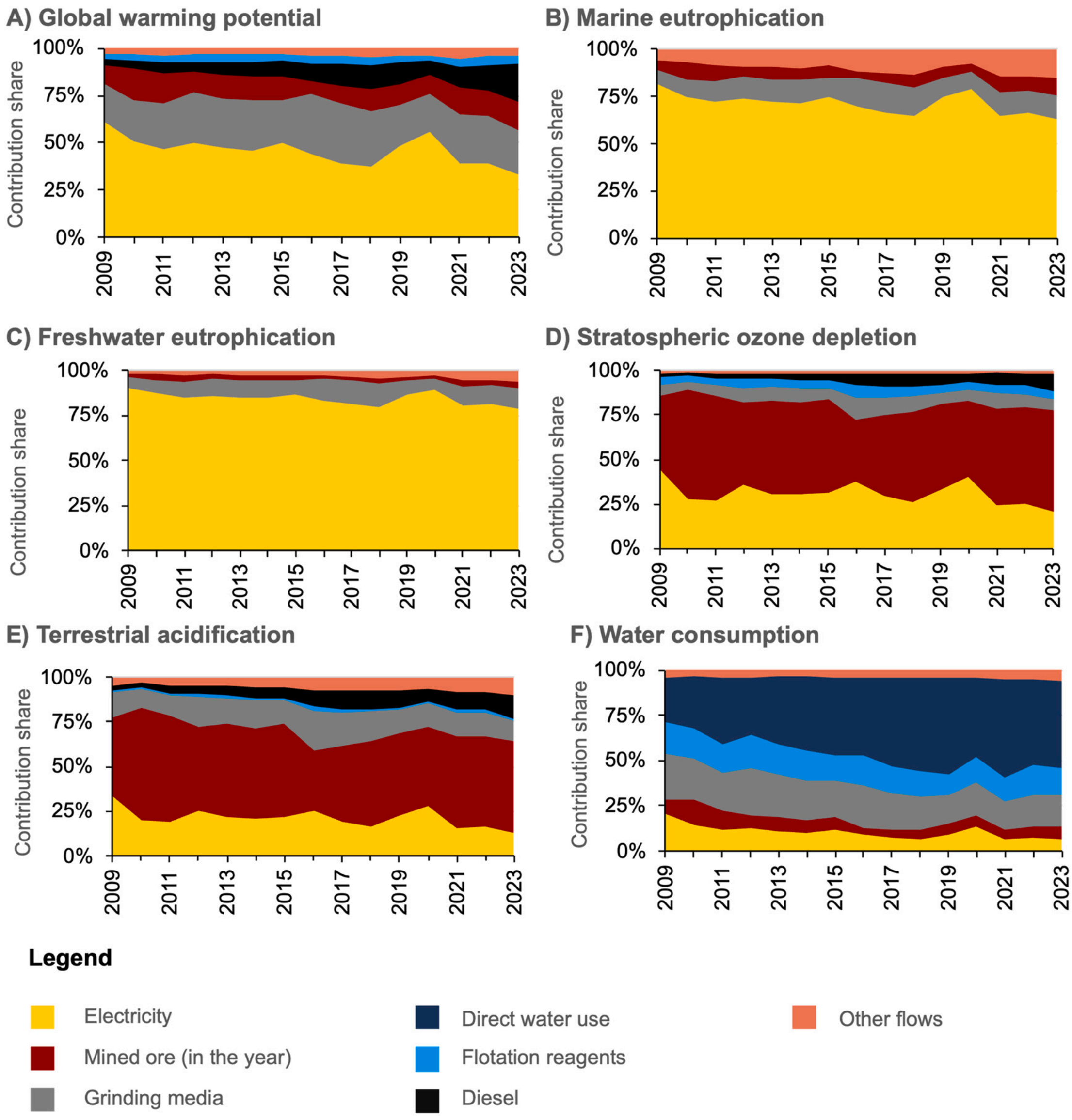

Fig. 6. Dynamic hotspot analysis of Spodumene concentrate production in Greenbushes for selected impact categories

Regarding the water consumption indicator, the impacts trend upward across the period, with 2021 registering the worst performance, 110 % higher than 2009. Direct process water intake is the principal source, standing 280 % (1) and 360 % (2021) above the 2009 baseline. Across the assessment period, direct water intake dominated the input profile, averaging 42 % of total resource use. Grinding media and flotation reagents contributed 20 % and 15 %, respectively, followed by electricity at 10 % and mined ore at 7 %, on average. All remaining flows together accounted for less than 5 % as the mean share.

Regarding land use, impacts decline steadily from 53.9 m^2·a eq in 2009 to 41.2 m^2·a eq in 2019, then rebound sharply, peaking at 57.4 m^2·a eq in 2022 before easing to 55.4 m^2·yr eq in 2023. Flotation reagents (mean share around 42 %), tailings management (on average 20 %), mined ore (17 %), and direct beneficiation site expansion (13 %) are the principal contributors. The recent surge is linked to successive capacity expansions (CGP2, CGP3, CGP4, tailing remediation plant (TRP)) and the increased reagent use and tailings volumes that accompany lower-grade ore. All remaining flows together accounted for less than 9 % on average.

3.3. Stepwise regression and validation

The heat maps presented in Figs. 3 and 4 provide a comprehensive depiction of temporal variations in environmental impacts, pinpointing critical years with peak impacts and highlighting key categories that may require focused mitigation strategies. To gain deeper insights into the underlying factors and relationships influencing these outcomes, stepwise regression analysis was conducted to assess the significance of variable parameters across mining and processing operations. The range of these variable parameters is depicted in Figs. 7 and 8. Fig. 7 presents mining and processing variable parameters in 4 charts, respectively, A for grade change during the study period, B for other mining parameters, C for overall recovery and yield of processing operation, and D for the overall concentration ratio. Fig. 8 displays the input ore quality and exact concentrate grade for each processing plant in the A and B charts, respectively, while the charts C and D provide process analytics for the TGP, CGP1, and CGP2, including concentration ratio, yield, and recovery.

The stepwise regression results for the GWP impact category of mining and processing operations are summarised in Tables 5 and 6, respectively. The optimal parameter fits for the GWP are presented in

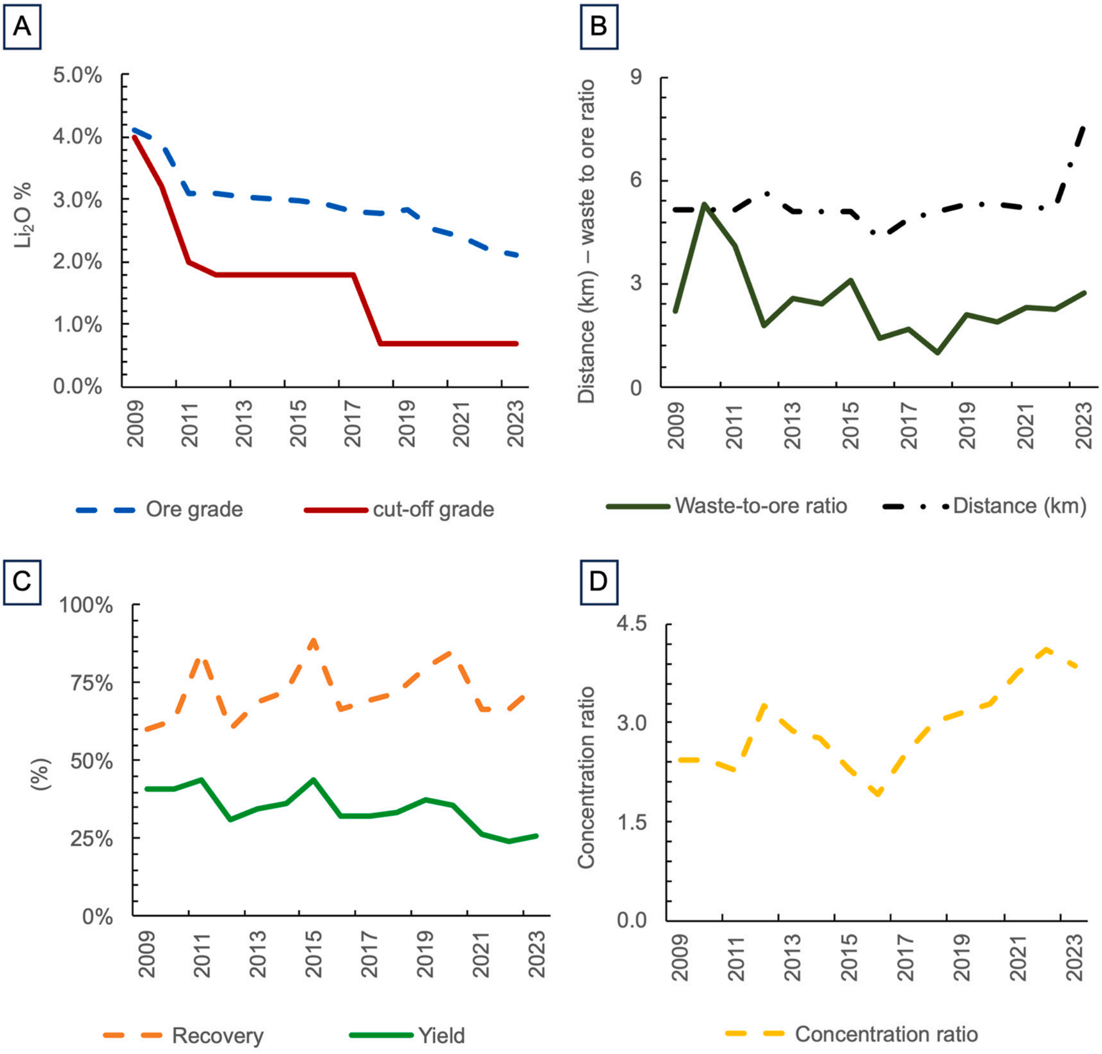

Fig. 7. Range of variable parameters between 2009 and 2023, A and B) mining, C and D) processing.

Eqs. (1) and (2), corresponding to the production of 1 t of Spodumene ore and 1 t of Spodumene concentrate, where WO, G and Y, respectively, represent waste-to-ore ratio, ore grade and processing yield. These equations represent the best-fit models for understanding the key contributors to the carbon footprint in these processes. Regression equations for all environmental impact categories of the ReCiPe midpoint 2016 method for Spodumene ore and Spodumene concentrate production are provided in SI-3.

$$\mathrm{GWP\ (ROM)} = 4.534 + 2.748\ \mathrm{WO} \tag{1}$$

$$\mathrm{GWP\ (SC6)} = 589.0 - 20812\ \mathrm{G} + 729\ \mathrm{Y} \tag{2}$$

The regression analysis for mining operations highlights the critical influence of the waste-to-ore ratio. Fig. 9 includes the Pareto chart of standardised effects and the normal probability plot, confirming the waste-to-ore ratio as the most impactful parameter. This finding underlines the importance of mining techno-economic factors like cut-off grade and waste-to-ore ratio in the carbon dioxide equivalent of the ROM and the necessity of attention to underground mining in regard to decreasing both global warming potential and land use of the Greenbushes mine. Also, Fig. 10 illustrates the Pareto chart of standardised effects and the normal probability plot, further confirming ore grade as the dominant factor. The SC6 regression analysis findings emphasise the critical role of ore grade in mitigating the environmental impacts of the Greenbushes plant, providing a basis for targeted process optimisation in Spodumene concentrate production.

The regression analysis results for the mining operation and Eq. (1) reveal the importance of the waste-to-ore ratio parameter as the most significant variable. It is worth noting that almost all these mining variable parameters are interconnected to each other to an extent. For instance, the reduction of cut-off grade due to increasing market demand and price of the mineral commodity gives economic feasibility to some of the deposits or of operating deposit zones (like C2 and Kapanga pits in Greenbushes), which were not feasible earlier. This change usually continues by increasing the length of the distance from the mine exploitation site to the waste dump and ore stockpile. The overall haulage per tonne of ore increases considerably. Consequently, one of the mitigation methods for mining activity is to switch to underground mining, where less waste materials need to be mined. In addition, the grade of mined ore would be higher and could further reduce the environmental impacts of processing operations.

For SC6 production, Eq. (2) indicates that a decline in ore grade significantly worsens the carbon footprint. Interestingly, the positive coefficient for the yield suggests that a lower yield would reduce the carbon footprint. It may appear to be counterintuitive at first glance, but this is mainly driven by the change in grinding and processing technology. Specifically, the old processes at TGP and CGP1 have higher feed ore and concentrate grades, thus a higher yield compared to CGP2 and,

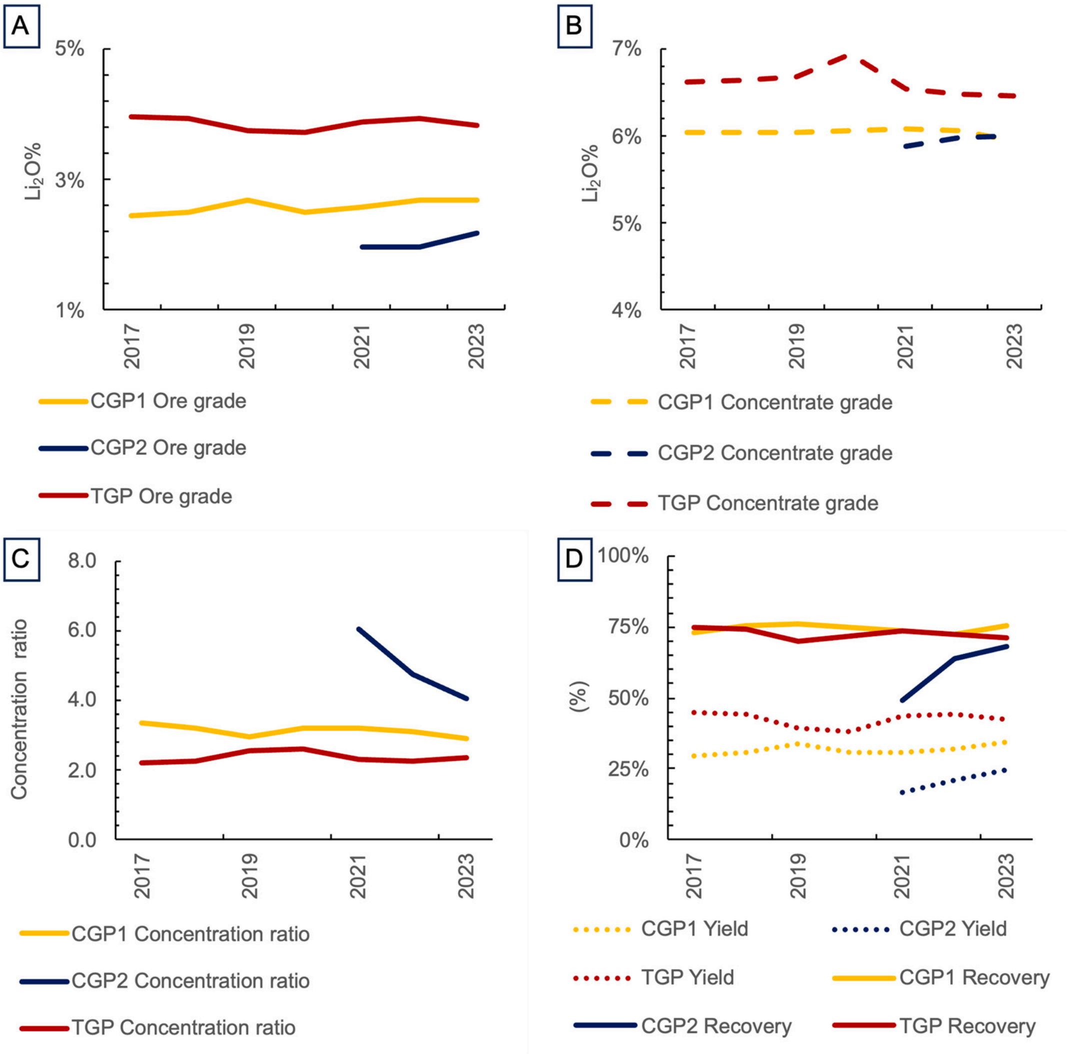

Fig. 8. Performance parameters of Greenbushes processing plants within 2017–2023, A) ore grade, B) concentrate grade, C) concentration ratio, D) yield and recovery rate of each operating processing plant.

Table 5
Stepwise regression analysis of Spodumene ore.

	Step 1		Step 2		Step 3	
	Coef	P	Coef	P	Coef	P
Constant	3.12		4.369		4.534	
Waste-to-ore ratio	2.597	0.000	2.644	0.000	2.748	0.000
Cut-off grade	32.8	0.198	26.0	0.258		
Distance	0.237	0.457				
S		0.739624		0.726991		0.738428
R-sq		95.32 %		95.07 %		94.49 %
R-sq(adj)		94.04 %		94.25 %		94.06 %

Bold data represent the parameters for mining operations.

in the future, CGP3 and 4. However, TGP and CGP1 use ball milling for grinding operation, which is more energy intensive compared to high-pressure grinding rolls (HPGR) utilised in CGP 2, 3 and 4. A potential mitigation strategy could involve blending high-grade ore intended for TGP and CGP1 to CGP2, thereby improving overall recovery across the plants.

To further demonstrate the validity of the derived regression models, the actual and predicted GWP values over the studied period are compared and presented in Fig. 11. The key parameters were derived from SK-1300 reports prepared by SRK Consulting and NI43-101 technical reports prepared by Behre Dolbear Australia. The carbon footprint of mining operations showed an accurate prediction, whereas there is a consideration margin for the Spodumene concentrate in the initial years. These errors are because only TGP was utilised till 2011, whereas Eq. (2) incorporates all other processing plants (i.e. CGP 1 and CGP 2). Thus, the margin reduces significantly after 2021, corresponding to the year of commissioning CGP 2. The SK-1300 reports also project future options until the end of the current project's lifetime, which enables a prediction of the carbon footprint for the Greenbushes options until 2041. According to our model, a clear increasing trend would be expected mainly owing to the decline in the ore grade to around 1.6 %.

3.4. Benchmarking

Over the 15-year window examined here (2009–2023), the greenhouse gas profile of Spodumene operations at Greenbushes was anything but static. The carbon footprint of mining one tonne of Spodumene ore started at 11 kg CO_2 eq in 2009, spiked to 20 kg CO_2 eq during the C1/C3 pit expansions (2010–2011), bottomed out at 8 kg CO_2 eq in 2016, and settled at 12 kg CO_2 eq by 2023. For Spodumene concentrate production, the trajectory differed; Early production from high-grade ore (288 kg CO_2 eq/t SC6 in 2009) fell to 228 kg CO_2 eq in 2011, then rose

Table 6
Stepwise regression analysis of Spodumene concentrate.

	Step 1		Step 2		Step 3		Step 4	
	Coef	P	Coef	P	Coef	P	Coef	P
Constant	176		318		300		589.0	
Yield	1095	0.328	705	0.081	727	0.020	729	0.029
Ore grade	−13,046	0.297	−14,723	0.106	−14,401	0.041	−20,812	0.005
Concentration ratio	36.9	0.401	39.4	0.227	38.0	0.130		
Throughput	0.0545	0.617						
Output	−0.211	0.607	−0.0081	0.830				
S		15.6836		13.4583		11.1505		15.0477
R-sq		97.21 %		95.89 %		95.77 %		89.73 %
R-sq(adj)		83.27 %		87.68 %		91.54 %		84.60 %

Bold data are significant parameters for processing operations.

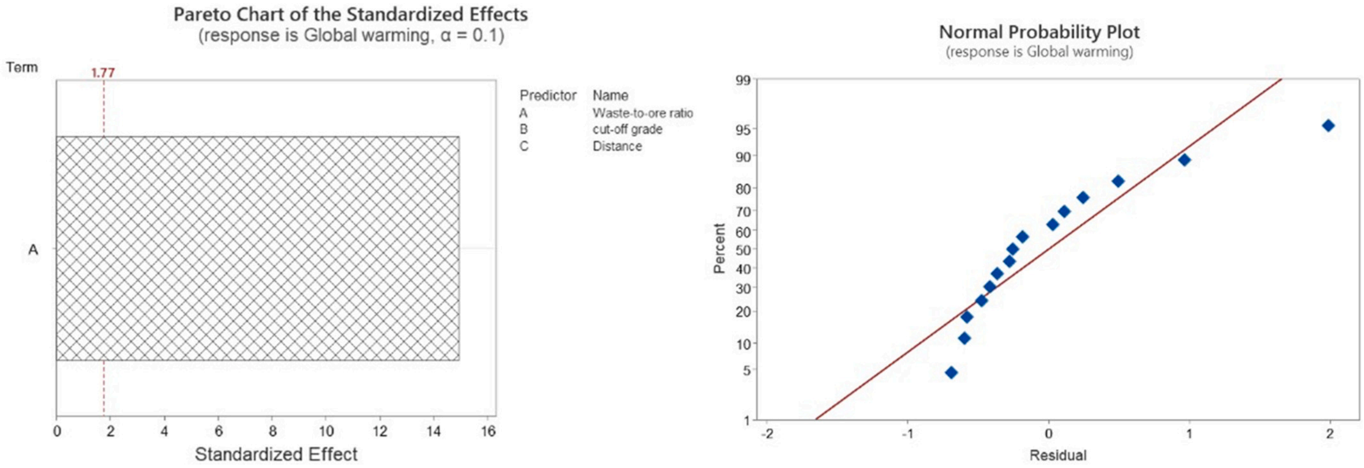

Fig. 9. Left) Pareto chart, and right) normal probability plot of Spodumene ore regression analysis.

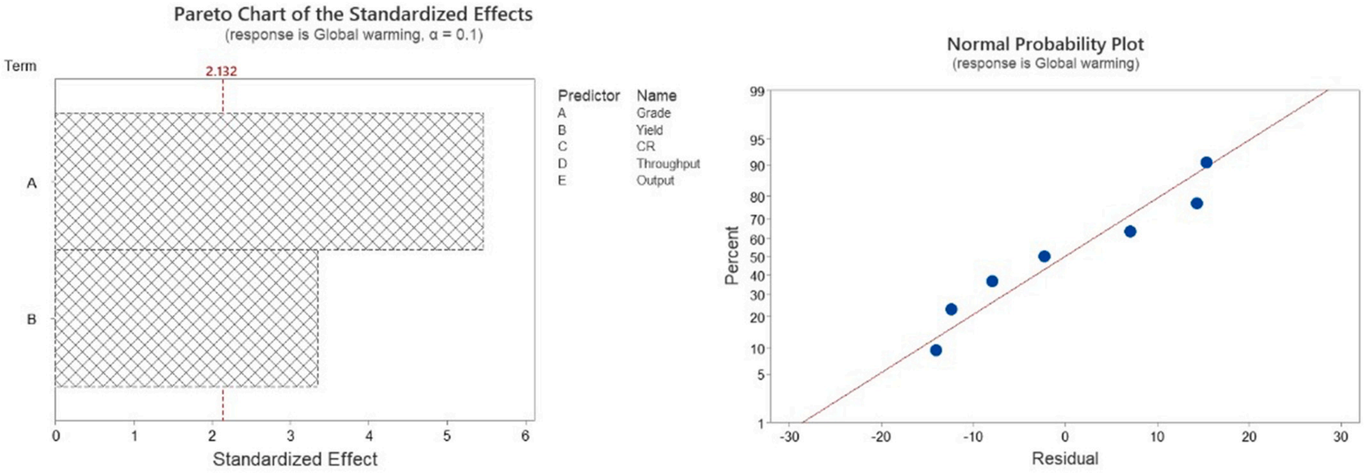

Fig. 10. Left) Pareto chart, and right) normal probability plot of Spodumene concentrate regression analysis.

gradually, albeit with year-to-year variability, to 326 kg CO_2 eq in 2023 as lower-grade feed, longer haul distances and higher reagent dosages took effect.

Published LCIs offer a useful benchmark but underscore the sensitivity of results to data quality and modelling assumptions. The widely used Frischknecht et al. (2007), built from iron ore mining and lime comminution data, yields 42 kg CO_2 eq per tonne SC6 and 2.1 kg CO_2 eq per kg lithium carbonate, values now recognised as low. Stamp et al. (2012), drawing on similar proxies, reported 38 kg CO_2 eq SC6 under “favourable” Australian conditions and 149 kg CO_2 eq per tonne SC6 for a hypothetical DRC scenario (Manono project); these LCIs have been replicated across many downstream battery studies. By contrast, Kelly et al. (2021) estimated 428 kg CO_2 eq per tonne SC6 for Australia and 20.4 kg CO_2 eq per kg lithium carbonate for Chinese conversion, potentially overestimating our 2011–2023 range (12.2–13.0 kg CO_2 eq per kg lithium carbonate when Kelly’s conversion factors are coupled with our mine-site data). Recent comparisons using ecoinvent 3.8 (e.g. Chordia et al., 2022) fall near the lower end (around 47 kg CO_2 eq per tonne SC6). Using the proxy LCIs of Stamp et al. and Laferrière et al., Ambrose and Kendall projected a cradle-to-gate footprint of 3.2 kg CO_2

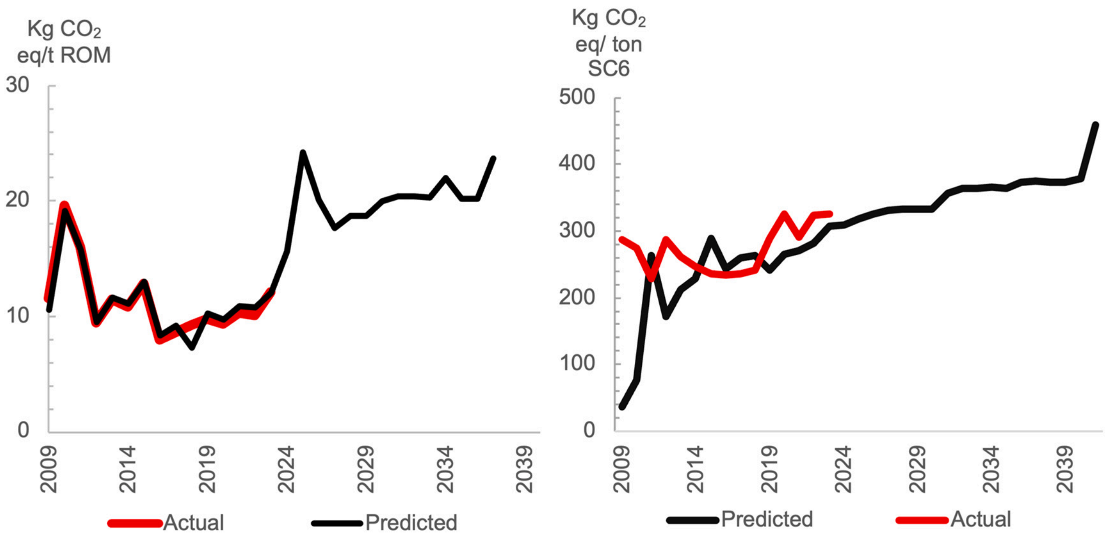

Fig. 11. Left) Actual vs predicted GWP for Spodumene ore, right) actual vs predicted GWP for Spodumene concentrate (SK = SK1300 - U.S. Securities and Exchange Commission file, NI = NI 43-101 - Canadian securities regulatory instrument).

eq per kg lithium carbonate in 2020, rising marginally to 3.3 kg CO_2 eq by 2100. This near-constancy reflects their use of static mine parameters, whereas our time-resolved dataset shows that changes in ore grade and pit geometry can swing the mining, processing and refining contributions by ±150 %, ±40 %, and ±6 %, respectively, within a 15-year study period.

Taken together, these discrepancies highlight two points. First, single-year or proxy-based LCIs risk misrepresenting a system whose impacts evolve with geology, technology and market demand. Second, combining our temporal-explicit, primary-data inventory narrows the uncertainty in assessing the environmental impacts of lithium-ion battery value chain.

4. Conclusion

Our dynamic, parameterised LCA of Spodumene ore and Spodumene concentrate production at Greenbushes (2009–2023) closes a persistent data gap in lithium-supply inventories by relying exclusively on primary operational records. This analysis reveals that electricity consumption and grinding media constitute over 50–81 % of the Greenbushes project's total carbon footprint, with diesel consumption rising from 3 % to 20.1 % over the study period due to mine and project expansion. Based on the parametrisation and regression analysis, waste-to-ore ratio and feed grade are the strongest drivers across most impact categories. These findings reinforced how incremental geology, mine design, and operating changes can affect the environmental burdens of mine and beneficiation site by well over an order of magnitude within a 15-year study period. Despite the strong statistical evidence in the regression analysis, the resolution of this analysis is limited to annual reports with a small number of observations, which causes uncertainties to the results. Studies with a higher time resolution and close monitoring of the mining and processing operations into the future would enhance the robustness of this parametric LCA.

Targeted strategies can mitigate these effects. Adopting emerging high-voltage pulse-fragmentation systems, such as I-Pulse or plasma-assisted blasting, would sharply cut emissions by replacing bulk explosives with electricity-driven rock breakage. Complementing this, deploying battery-electric or hydrogen-fuel-cell haul trucks and loaders would almost eliminate diesel-related CO_2 and NO_x, while sourcing site power from wind or photovoltaic micro-grids would further compress the operation's cradle-to-gate carbon footprint. Together, these technology shifts offer a credible pathway toward net-zero spodumene supply. Additionally, implementing advanced milling technologies with greater energy efficiency and reduced grinding media requirements could mitigate impacts across key categories, including global warming potential and resource scarcity. Enhanced data quality and detailed future scenario studies would further strengthen the robustness of these assessments, equipping decision-makers with accurate insights to identify and address the specific impacts linked to lithium production as future research.

This improved transparency forms a foundation for responsible mining practices and supports the development of informed policies, particularly within Australia's mineral sector. By shedding light on essential environmental trade-offs, this research serves as a critical tool for stakeholders, enabling strategic decisions that balance economic objectives with environmental responsibility. Ultimately, this study promotes a more sustainable approach to mineral supply chains, reducing the environmental impacts associated with Australia's integral role in the global market.

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CRediT authorship contribution statement

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

Declaration of Generative AI and AI-assisted technologies in the writing process

We disclose the use of ChatGPT to improve the readability and language of this paper.

Declaration of competing interest

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