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Integrated Process Development for Sustainable Lithium Extraction from Nigerian Pegmatite Ores: Process Optimization, Techno-Economic Analysis, and Environmental Assessment

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Abstract

Nigeria's lithium-bearing pegmatites could support local mineral processing and battery-material production, but commercial success depends on more than ore availability. A workable operation must address low feed grade, variable spodumene–mica mineralogy, energy demand, reagent recovery, water use and unstable lithium prices. This study develops an integrated process model for a representative Nasarawa-type pegmatite containing 1.08% Li_2O. The proposed route combines staged crushing, de-sliming, two-stage dense-medium separation, flotation of middlings, direct low-temperature NaOH roasting, counter-current water leaching, impurity removal and carbon-dioxide precipitation of lithium carbonate. Water, caustic solution and silicate-rich residues are partly recovered for reuse. Response-surface analysis was used to examine roasting temperature, NaOH-to-spodumene ratio and residence time. The sustainability-adjusted optimum was 333°C, a ratio of 1.47 and 83 minutes, producing a predicted lithium extraction of 97.5%. One tonne of ore yielded about 22.3 kg of lithium carbonate, representing an overall recovery of 83.5%. For a 200,000-tonne-per-year plant, annual output was estimated at 4,460 tonnes. Installed capital was projected at US$98.2 million, operating cost at US$6,460 per tonne, net present value at US$80.7 million, internal rate of return at 22.9% and minimum selling price at about US$10,600 per tonne. Environmental screening suggested that renewable electricity, heat recovery, caustic recycling and residue utilization could reduce climate impacts by nearly half. These results are design estimates and require pilot testing, residue assessment and local cost validation before investment. The model therefore provides a preliminary basis for comparing technical performance, profitability and environmental trade-offs within Nigeria's responsible, emerging domestic hard-rock

lithium industry sector.

Keywords: Lithium Carbonate, Nigerian Pegmatite, Spodumene, Dense-Medium Separation, Naoh Roasting, Process Optimization, Techno-Economic Analysis, Life-Cycle Assessment

1.0 INTRODUCTION

Lithium has moved from a specialty metal to a strategic input for electric mobility, stationary storage and digital infrastructure. The International Energy Agency projects a steep rise in lithium demand through 2040, even under stated policies, while also warning that supply concentration and project delays could create renewed deficits after the present period of market softness (International Energy Agency [IEA], 2025). Global mineral-commodity reporting likewise shows why diversification of mine and conversion capacity remains strategically important (U.S. Geological Survey [USGS], 2025). The implication for emerging producers is not simply that new mines are needed. Competitive projects must deliver consistent chemical products, remain viable through price cycles and avoid transferring the environmental burden of the energy transition to mining communities.

Nigeria is well placed to examine that challenge because lithium minerals occur within an extensive pegmatite belt that crosses several states. Recent work on a Nasarawa ore reported a feed grade of 1.08% Li_2O, with spodumene as the principal lithium mineral and quartz, feldspar and mica as the dominant gangue. The same study showed that coarse liberation permitted two-stage dense-medium separation to produce a 5.68% Li_2O concentrate at more than 80% lithium recovery, while rejecting a large proportion of low-grade waste before grinding (Wang et al., 2025). These findings are encouraging, but a saleable concentrate is only one stage in a longer value chain. The difficult and costly step is the conversion of a resistant aluminosilicate mineral into battery-grade lithium carbonate or lithium hydroxide.

Conventional spodumene refining normally converts naturally occurring α-spodumene to a more reactive β-phase at about 1,000–1,100 °C, followed by sulfuric-acid baking, water leaching, purification and precipitation. The route is technically established, yet its furnace duty, acid consumption, neutralization requirement and sulfate-rich residue create a heavy cost and emissions burden (Rioyo et al., 2022). Reviews of hard-rock lithium supply repeatedly identify high-temperature conversion as a major source of energy use and greenhouse-gas emissions (Asif et al., 2024, Chordia et al., 2022). For a Nigerian project, those weaknesses would be magnified by variable electricity reliability, imported process chemicals, exchange-rate exposure and limited infrastructure for handling aggressive liquid wastes.

Recent research has therefore shifted toward direct treatment of α-spodumene. Microwave-assisted calcination has achieved high lithium recovery with shorter heating periods (Rezaee et al., 2022). Salt roasting, dry chlorination, alkaline conversion and mechanochemical routes have also been examined (Fosu et al., 2022, Han et al., 2022; Ni et al., 2025). Of particular relevance is the low-temperature NaOH process developed by Subasinghe and Rezaee (2025), which formed water-soluble lithium-bearing phases at approximately 325 °C and recovered more than 99% of lithium through two-stage roasting and room-temperature water leaching. A later integrated assessment reported that this direct route could lower climate impacts and improve economic performance relative to conventional acid processing, although its profitability remains sensitive to scale, reagent recycle and product price (Sharifian et al., 2026).

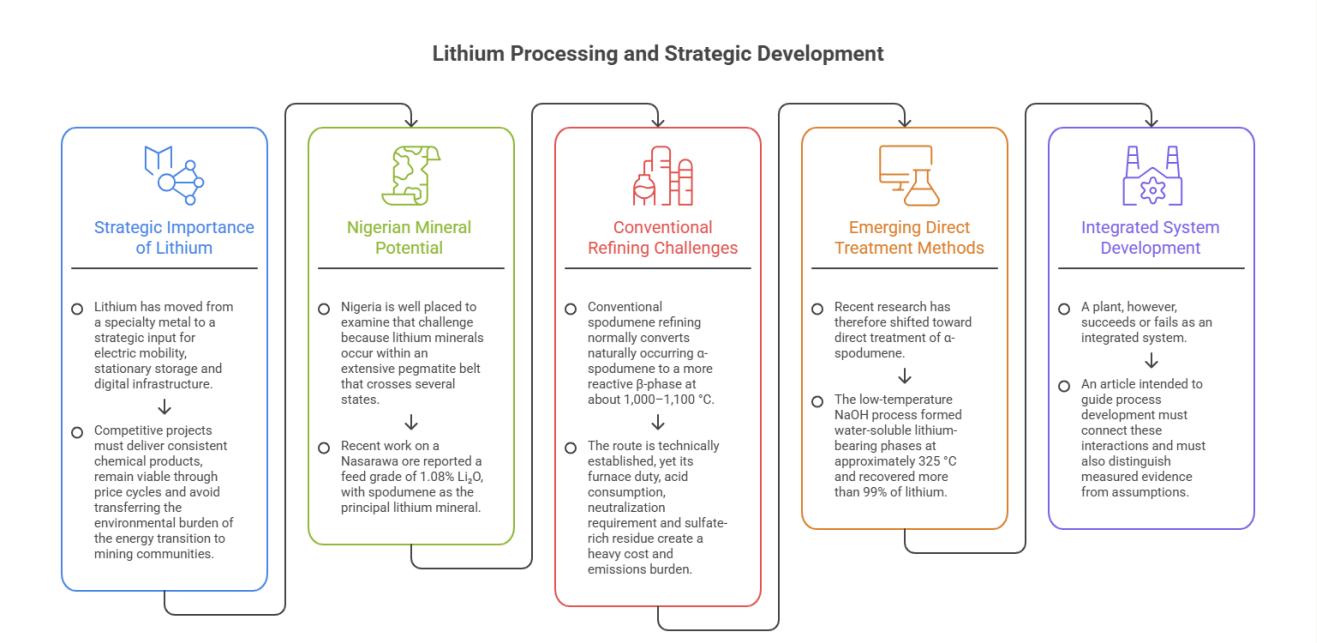

Figure 1: Processing Stages of Lithium Development

The research gap is therefore not the absence of isolated unit operations. Beneficiation, direct extraction, process economics and environmental assessment have usually been treated separately. A plant, however, succeeds or fails as an integrated system. A beneficiation decision alters the mass that enters the roaster; the roaster determines caustic demand and residue mineralogy; caustic recycle affects operating cost and water quality; and residue utilization can either create value or conceal a future liability. An article intended to guide process development must connect these interactions and must also distinguish measured evidence from assumptions.

2.0 STATEMENT OF THE PROBLEM

Nigeria has identified lithium-bearing pegmatites with potential to support local battery-material production, yet resources are exported or assessed only at the exploration stage. Existing studies often examine beneficiation, extraction, economics or environmental effects separately, leaving limited evidence on how these stages perform as one connected system under Nigerian conditions. Low ore grade, variable mineralogy, high energy demand, reagent losses, water use, residue disposal and unstable lithium prices may weaken project viability. Without an integrated process that is technically efficient, economically realistic and environmentally responsible, investment decisions remain uncertain. This study therefore addresses the need for an optimized Nigerian lithium-processing framework.

3.0 OBJECTIVES OF THE STUDY

This study develops an integrated, sustainability-oriented processing framework for Nigerian pegmatite ores. It has four objectives:

1. to establish a technically credible flowsheet from low-grade ore to lithium carbonate;
2. to optimize the direct roasting–leaching stage using a transparent response-surface model;
3. to evaluate mass balance, capital requirement, operating cost and project value at a defined scale; and
4. to screen the principal environmental burdens and identify practical reduction measures.

4.0 CONCEPTUAL REVIEW

4.1 Lithium-Bearing Pegmatite Ores

Lithium-bearing pegmatites are coarse crystalline rocks in which lithium may occur mainly as spodumene, petalite or lithium-rich mica. Their usefulness cannot be judged from bulk lithium grade alone. Quartz, feldspar, muscovite and accessory minerals influence liberation, separation behaviour, reagent demand and the character of the waste produced. Roy et al. (2023) showed that spodumene pegmatite can contain a complex mixture of major and trace minerals and that processing changes the proportion of spodumene without necessarily removing every environmentally relevant component. This means that Nigerian ores should be examined deposit by deposit rather than treated as one uniform feed. A sound characterization programme should establish mineral phases, grain size, lithium distribution, degree of liberation and the presence of elements that may enter concentrates, water or residues. In this study, lithium-bearing pegmatite is therefore viewed as a variable mineral feed whose commercial value depends on how efficiently and safely its lithium can be recovered.

4.2 Beneficiation and Pre-Concentration

Beneficiation is the stage where barren or weakly mineralized material is removed before expensive chemical treatment begins. Typical operations include crushing, screening, desliming, dense-medium separation and flotation. Their usefulness depends on particle size, density contrast and the extent to which spodumene has been released from quartz, feldspar and mica. Wang et al. (2025) demonstrated that a two-stage dense-medium circuit could produce a 5.68% Li_2O concentrate at more than 80% lithium recovery while rejecting roughly 70% of the feed as low-grade waste. The result shows why early gangue rejection can reduce the tonnage sent to grinding, roasting and leaching. It does not, however, mean that the same settings will suit Nigerian pegmatites. Local mineralogy, weathering and mica content may change separation efficiency. Beneficiation is therefore treated here as a plant-wide control point because its performance shapes energy use, reagent consumption, product recovery and tailings volume throughout the process.

4.3 Lithium Extraction from Spodumene

Lithium in natural α-spodumene is held within a resistant aluminosilicate structure, so the mineral must be altered before lithium can be dissolved and recovered. The established industrial route relies on high-temperature phase conversion, acid baking and water leaching. Recent work has explored direct alkaline treatment to avoid part of this thermal burden. Han et al. (2022) screened several roasting reagents and obtained 71% water-leach recovery and 88% total recovery with NaOH at 320°C under conditions that had not yet been optimized. Subasinghe and Rezaee (2025) later used two-stage NaOH roasting at about 325°C followed by room-temperature water leaching, reporting more than 99% lithium recovery. These findings make direct alkaline extraction attractive for Nigerian process development. Nevertheless, a high laboratory recovery is only one requirement. Reagent regeneration, corrosion, impurity removal, water balance, product purity and stable continuous operation must also be demonstrated before the route can be considered commercially dependable.

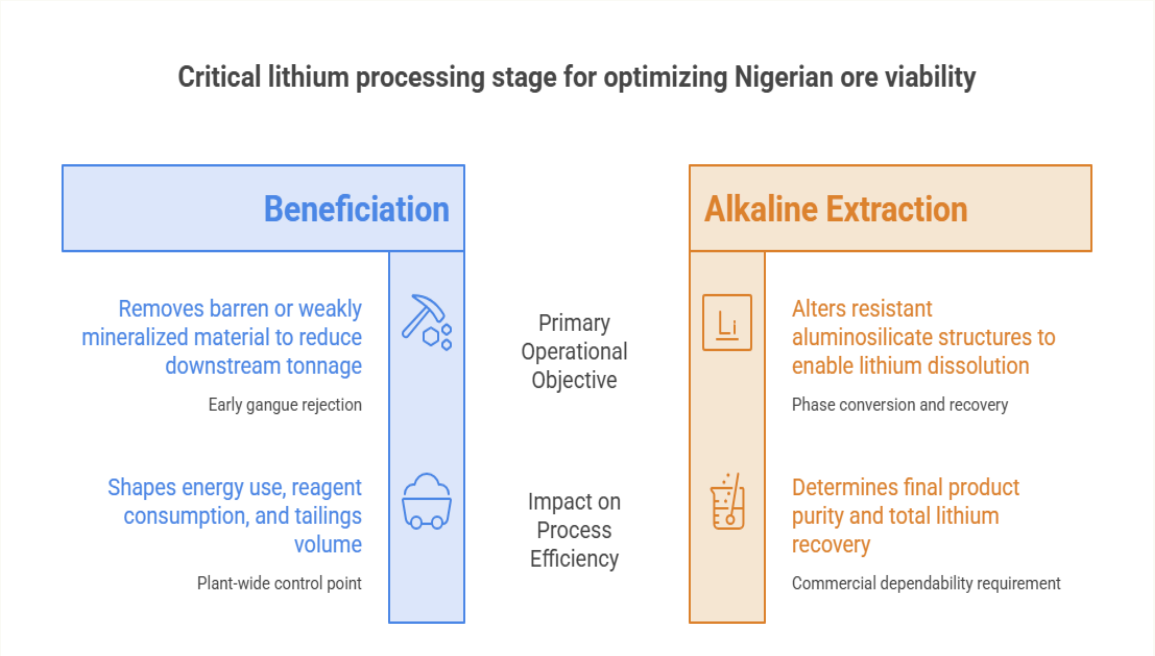

Figure 2: Lithium Optimization Stages for Nigerian Ore Viability

4.4 Integrated Process Development and Optimization

Integrated process development examines the entire route from run-of-mine ore to saleable lithium product instead of improving each operation in isolation. This approach matters because one decision can shift cost or environmental pressure to another section of the plant. Stronger pre-concentration reduces roaster feed but may also lose fine lithium minerals. Roasting temperature affects extraction, fuel demand and residue composition, while water-leaching conditions influence solution strength, washing requirements and caustic recovery. Subasinghe and Rezaee (2025) linked low-temperature roasting with rapid water leaching and a counter-current flowsheet, illustrating the value of designing connected operations. Optimization should therefore seek a practical compromise rather than the highest extraction figure alone. Variables such as temperature, NaOH-to-spodumene ratio and residence time can be studied through response-surface methods, while the preferred setting can be selected using recovery, energy, reagent-use and waste criteria. For Nigerian ores, measured mineralogical and pilot data should gradually replace literature-based assumptions as development proceeds.

4.5 Techno-Economic Analysis

Techno-economic analysis translates process performance into an investment case. It combines ore throughput, recovery, equipment capacity, energy and reagent needs, labour, maintenance and product output to estimate capital and operating costs. Common decision measures include net present value, internal rate of return, payback period and minimum selling price. These indicators matter greatly in lithium projects because profitability can shift with ore grade, plant utilization, reagent prices and the value of lithium carbonate. Sharifian et al. (2026) compared conventional, direct alkaline and electrochemical spodumene routes and found that the direct NaOH route produced lower annual operating costs and stronger returns under their assumptions. Those results cannot be transferred directly to Nigeria. Power reliability, fuel supply, transport, financing, taxation, imported equipment and exchange-rate exposure may alter project performance. Accordingly, techno-economic analysis is used here as a transparent decision tool supported by sensitivity and uncertainty testing, rather than as a single fixed prediction of commercial success.

4.6 Environmental Assessment and Circularity

Environmental assessment examines where lithium production places pressure on energy, water, chemicals, air emissions and solid residues. Its purpose is not merely to describe one route as "green," but to identify burdens that may be reduced, shifted or overlooked. Roy et al. (2023) found that the behaviour of spodumene-processing materials varied with mineralogy, particle size and test conditions, showing why drainage and residue performance must be measured. Sharifian et al. (2026) reported lower climate impacts for direct NaOH extraction than for conventional high-temperature acid processing, largely because heat and acid requirements were reduced. Circular practices may strengthen this advantage through heat recovery, water reuse, caustic regeneration and carefully tested residue products. Ibsaine et al. (2024), for example, demonstrated that aluminosilicate lithium residues could be converted into zeolite with promising technical and economic results. Such reuse is credible only when product quality, leachability, market demand and transport needs are verified under Nigerian operating conditions

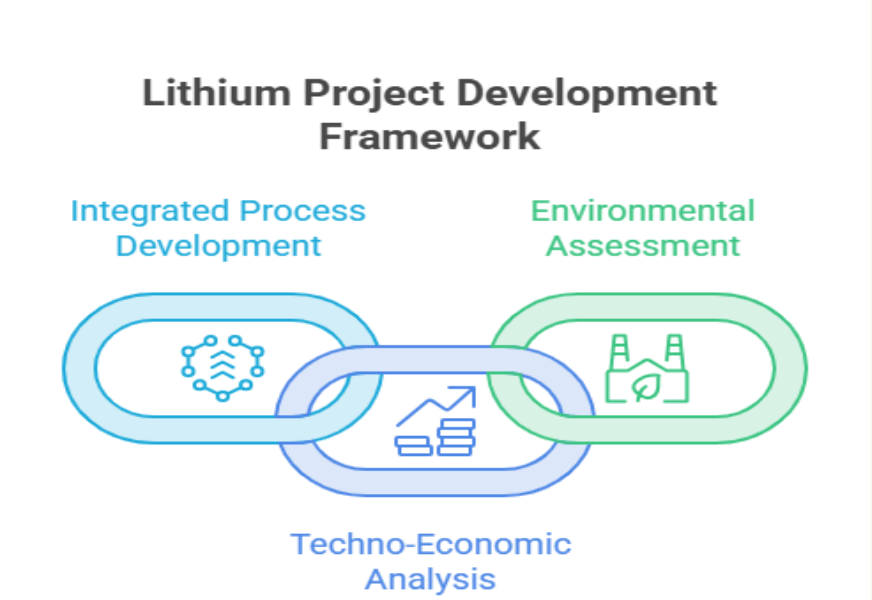

Figure 3: Strategic Framework for Lithium Development

Table 1: Review of related literature

Study	Method or process focus	Principal findings	Limitation, gap and relevance to the present study
Wang et al. (2025)	Heavy-liquid tests, numerical modelling and two-stage dense-medium cyclone separation.	Produced a 5.68% Li2O concentrate at more than 80% lithium recovery and rejected about 70% of the mass as 0.13% Li2O waste. The work established that coarse pre-concentration is technically feasible for Nigerian ore.	The study stopped at beneficiation and did not evaluate roasting, leaching, product purification, project economics or environmental impacts. It supplies the strongest local ore basis for the integrated flowsheet developed in the present study.

Kundu et al. (2023)	Comprehensive review of geology, dense-medium separation, flotation, thermal activation and hydrometallurgical extraction.	Concluded that beneficiation route selection must reflect liberation size and mineralogy. Dense-medium separation is effective for coarse liberation, while flotation remains important for fine and middlings recovery.	The review did not integrate ore variability with downstream mass balance, TEA or LCA. It supports the staged DMS-plus-flotation strategy used for the Nigerian process model.
Rioyo et al. (2022)	Review of alpha-to-beta conversion, sulfuric-acid baking, water leaching, purification and crystallization.	Identified high-temperature pretreatment, acid consumption and large residue generation as the main weaknesses of the established route, while noting its industrial maturity and high recovery.	The article is a route review rather than an optimized integrated plant study. It provides the conventional benchmark against which the proposed lower-temperature alkaline route is compared.
Rezaee et al. (2022)	Microwave-assisted calcination followed by acid roasting and leaching; microwave power was varied from 0.5 to 3.0 kW.	At 2.0 kW, lithium recovery reached about 97%. Microwave treatment accelerated heating and reduced the co-dissolution of Fe, Na and Ca relative to conventional heating.	The process still depends on high-temperature phase transformation and acid treatment, and industrial microwave scale-up remains uncertain. It demonstrates the value of process intensification but not a complete solution to thermal and reagent burdens.
Han et al. (2022)	Salt/alkali roasting, water leaching and acid polishing supported by thermodynamic and solution-chemistry modelling.	NaOH was the most effective reagent. Under non-optimized conditions of 320 degrees C, a 1.5:1 NaOH-to-spodumene ratio and 2 h roasting, water recovery reached 71% and total recovery reached 88%.	Recovery depended partly on acid leaching and the study called for parameter optimization and by-product recovery. It established the chemical basis for direct low-temperature NaOH treatment adopted in the present study.
Fosu et al. (2022)	Direct dry chlorination with CaCl2 followed by water leaching and thermodynamic/kinetic analysis.	At a CaCl2-to-spodumene molar ratio of 2.0, 1000 degrees C and 60 min, almost 90% of lithium was converted to LiCl and about 85% entered the leach solution.	The process remained thermally severe and experienced lithium loss to off-gas, with added corrosion and gas-management requirements. It is technically relevant as a direct route but less compatible with the lower-risk Nigerian design criteria.

Zhang et al. (2023)	CaO-assisted activated roasting combined with sulfuric-acid leaching and thermodynamic analysis.	A lithium leaching yield of 96.18% was obtained using 20% CaO, roasting at 1200 degrees C for 1.5 h and leaching in 120 g/L H2SO4 at 80 degrees C.	Although recovery was high and acid consumption was lower than the conventional route, the process retained very high roasting temperature and acidic purification. It illustrates the recovery-energy trade-off addressed by the present optimization.
Jiang et al. (2024)	Microwave-enhanced sulfate roasting using ferrous sulfate, potassium sulfate and CaO, followed by water leaching.	The optimized route achieved 95.9% lithium leaching at 775 degrees C and reduced microwave heating time from 43 to 20 min compared with conventional heating.	The feed mineral was lepidolite rather than spodumene and the additive system is chemically different. Nevertheless, the study shows how microwave fields can reduce heating time and improve process intensity in lithium silicates.
Ni et al. (2025)	Binary Na2SO4-CaO composite-salt roasting followed by water leaching, with thermodynamic and kinetic modelling.	At a spodumene/CaO/Na2SO4 mass ratio of 1:0.1:0.8, 900 degrees C for 2 h and leaching at 60 degrees C, lithium recovery reached 95.45%.	The temperature was lower than conventional decrepitation but remained high, and sulfate-bearing residues still require management. It provides a useful intermediate benchmark between acid baking and very low-temperature NaOH roasting.
Subasinghe and Rezaee (2025)	Two-stage NaOH roasting near 325 degrees C, room-temperature water leaching, kinetic modelling and process-flowsheet development.	The route converted spodumene into water-soluble lithium-bearing phases and achieved more than 99% cumulative lithium recovery. Water leaching was rapid and avoided sulfuric-acid baking.	The evidence was laboratory/pilot oriented, while continuous recycle behaviour, impurity build-up, corrosion, product purification, TEA and LCA required further validation. This is the principal extraction chemistry adopted and extended by the present integrated study.
Pimassoni et al. (2025)	Ball milling with NaOH followed by water leaching; factorial design and ANOVA assessed ball size and NaOH-to-ore ratio.	Lithium extraction ranged from 20% to about 74-75%, with the highest result at a NaOH-to-ore ratio of 8.5 and 10 mm milling media. The method bypassed thermal decrepitation and acid leaching.	The high NaOH demand and lower recovery limit immediate scale-up. The study confirms the promise of non-thermal activation but shows why the present work selected controlled low-temperature roasting rather than intensive mechanochemistry.

Wang et al. (2021)	Hydrothermal conversion of residue into nano-kaolinite, xonotlite and related silicate products.	Demonstrated that lithium slag can be transformed into higher-value mineral products and that residue need not be treated solely as waste.	The work did not establish market size, transport burden, product certification or long-term leachability. It supports residue valorization in the present circularity model, but only after product and environmental qualification.
Chordia et al. (2022)	Comparative life-cycle review using databases, literature and project inventories.	Showed that environmental burdens depend strongly on source grade and process configuration. Spodumene-derived lithium contributes materially to battery climate impacts because thermal processing is energy intensive.	The study compared global supply routes but did not model a Nigerian grid, local water conditions or a low-temperature direct process. It provides the environmental benchmark and hotspot logic used in the present assessment.
Asif et al. (2024)	Review of extraction technologies, decarbonization options, waste management and circular-economy strategies.	Argued that conventional hard-rock lithium processing places heavy pressure on energy, reagents and waste systems, and recommended process simplification, low-carbon energy and by-product utilization.	The work is strategic and review-based rather than a project-specific process model. Its circular-economy framing informed the heat recovery, reagent recycle and residue-use scenarios in the present study.
Sharifian et al. (2026)	Integrated cradle-to-gate LCA, TEA and Monte Carlo uncertainty analysis at 1-10 t/day product scales.	The direct NaOH route reduced global warming potential by 59% relative to the conventional route and, at 1 t/day, achieved a 41% rate of return and US$18.9 million NPV, with lower annual operating cost.	The model used U.S.-based prices and excluded mining/beneficiation from its system boundary. It strongly supports joint TEA-LCA evaluation, while the present study extends the boundary to Nigerian ore upgrading, local scale assumptions and residue management.

4.7 Gap in Literature

Recent studies have improved individual stages of hard-rock lithium processing, but an integrated Nigerian framework remains limited. Wang et al. (2025) demonstrated that dense-medium separation can upgrade low-grade Nigerian spodumene and reject substantial gangue; however, their analysis ended at beneficiation. Subasinghe and Rezaee (2025) reported very high recovery through low-temperature NaOH roasting and water leaching, yet continuous reagent recycle, impurity build-up, corrosion and product

purification were not fully resolved. Conventional and intensified routes reviewed by Rioyo et al. (2022) and Rezaee et al. (2022) still involve considerable thermal or chemical demand. Environmental studies, including Chordia et al. (2022), show that spodumene processing is strongly influenced by energy intensity, while Sharifian et al. (2026) combined techno-economic and life-cycle analysis using non-Nigerian assumptions. Therefore, a gap exists for an ore-to-product study that jointly optimizes Nigerian pegmatite beneficiation, lithium recovery, mass and energy balances, project economics, environmental impacts, residue utilization and scale-up requirements.

5.0 MATERIALS AND METHODS

5.1 Research design and system boundary

The study used a process-systems design rather than a laboratory experimental design. Recent peer-reviewed results were translated into a linked mass, energy, economic and environmental model. The functional basis was one tonne of delivered pegmatite ore, while the commercial model used 200,000 t ore per year and 330 operating days. The boundary began at ore reception and ended with dried lithium carbonate. Mine development, overburden removal, employee housing, downstream cathode manufacture and battery use were excluded. Their exclusion should be reconsidered in a full feasibility study, particularly where mine haulage or diesel generation is material.

Data were classified in three groups. Measured values included the Nigerian ore grade and published dense-medium separation performance. Literature-derived values included direct NaOH roasting temperature and attainable leaching recovery. Engineering assumptions included the additional recovery from middlings flotation, reagent recycle, plant availability, installed cost and Nigerian utility prices. Each assumption was made visible so that it can be replaced as local evidence becomes available. This treatment avoids the false precision that occurs when a process simulation is presented as if it were pilot data.

5.2 Integrated Process Description

Run-of-mine material is crushed to below 8 mm and screened at 0.5 mm. The coarse fraction enters two-stage dense-medium cyclones. High-density concentrate proceeds to extraction, low-density discard is washed to recover ferrosilicon, and middlings are milled to approximately 150 µm before desliming and flotation. Magnetic recovery returns dense-medium solids to the circuit. Process-water clarification is positioned close to the concentrator because poor control of slimes and medium density would quickly reduce separation sharpness.

The combined concentrate is dried, blended with NaOH and fed to an indirectly heated, corrosion-lined roaster. A two-stage arrangement is retained because the first water wash removes the reacted shell and exposes an unconverted core for the second treatment. The model assumes a sustainability optimum in the 330–335 °C region rather than the highest-recovery point, because the small recovery gain obtained from higher reagent dosage and temperature may not justify additional cost and impact. Heat is recovered from hot solids and exhaust gas to preheat feed and generate low-pressure process heat.

Roasted solids are leached in a counter-current arrangement at ambient to moderate temperature. Fast lithium dissolution permits short contact time, but industrial design must allow for mixing, solids settling and scale formation. Pregnant liquor is clarified and treated sequentially for aluminium, iron, calcium and magnesium control. Carbon dioxide is then introduced to precipitate lithium carbonate. Mother liquor and wash water are returned after sodium recovery and impurity bleed. The product is filtered, washed and dried. A quality laboratory verifies lithium carbonate purity, sodium, calcium, magnesium, iron, moisture and particle size before release.

The residue circuit separates coarse unreacted silicates, washed extraction residue and water-treatment

solids. Coarse DMS rejects may have aggregate or backfill value because it has not been chemically altered. Extraction residue requires a more conservative pathway: repeated washing, pH control, total and leachable metal analysis, mineralogical testing and performance trials in cementitious products. Material that fails product or environmental criteria must be placed in an engineered facility rather than marketed as a by-product.

5.3 Process-optimization Model

A three-factor response-surface model was constructed for direct roasting. The factors were temperature (300–350 °C), NaOH-to-spodumene mass ratio (1.2–1.8) and residence time (45–105 min). The ranges were selected around the low-temperature conditions reported by Han et al. (2022) and Subasinghe and Rezaee (2025). A Box–Behnken design generated 17 process points. Because raw experimental data for Nigerian concentrate were unavailable, responses were generated from a literature-calibrated quadratic simulator and constrained to remain within physically credible recovery limits. The fitted statistics therefore describe the internal design space; they are not substitutes for replicated experiments.

The coded quadratic model took the following form, where x_1, x_2 and x_3 denote temperature, NaOH ratio and time, respectively. A desirability function combines recovery with penalties for reagent dosage and thermal demand. Recovery received the highest weight because under-extraction enlarged recycle and residue inventories; reagent and energy penalties prevented the mathematical optimum from drifting toward the upper limits of all factors.

$$Y = \beta_0 + \Sigma\beta_i x_i + \Sigma\beta_{ii} x_i^2 + \Sigma\beta_{ij} x_i x_j \quad (1)$$

$$D = d_r^{0.55} \times d_{low}^{0.25} \times d_e^{0.20} \quad (2)$$

Here, Y is lithium extraction, D is overall desirability, d_r is the recovery desirability, d_{low} is the low-NaOH desirability and d_e is the low-energy desirability. The selected operating point was the maximum D, not the maximum recovery alone. Pilot testing should refit the coefficients using actual Nigerian concentrate and should include impurity dissolution, cake filtration and caustic-recycle responses.

Table 2. Factors and levels used in the literature-calibrated optimization

Factor	Symbol	Low (−1)	Centre (0)	High (+1)
Roasting temperature (°C)	x_1	300	325	350
NaOH/spodumene mass ratio	x_2	1.20	1.50	1.80
Residence time (min)	x_3	45	75	105

5.4 Mass and Energy Balance

Lithium was tracked as Li_2O through beneficiation and extraction, then converted to Li_2CO_3 using the molecular-mass ratio 73.89/29.88. The overall product yield was calculated from feed grade, beneficiation recovery, leaching recovery and precipitation recovery. Water, caustic and energy inventories were estimated per tonne of ore and scaled to annual production. The model assumed 70% effective NaOH recovery after liquor conditioning and 75% process-water recycling. These targets are demanding but central to the route's sustainability; failure to achieve them would materially increase both cost and environmental burden.

$$m(Li_2CO_3) = m(ore) \times G(Li_2O) \times \eta_\beta \times \eta_{leach} \times \eta_{ppt} \times 2.473 \quad (3)$$

$$\eta_{overall} = \eta_\beta \times \eta_{leach} \times \eta_{ppt} \quad (4)$$

5.5 Techno-Economic Method

The techno-economic analysis used a Class 4 screening estimate suitable for comparing development options, not for financing. Total installed capital covered crushing and DMS, flotation, roasting, leaching and purification, product finishing, water and residue facilities, utilities, engineering and contingency. The financial model assumed a 15-year operating life, 10% real discount rate, 30% income tax, straight-line depreciation and US$2.0 million per year sustaining capital. A constant lithium-carbonate price of US$14,000 t^{-1} was used only as a scenario input; it should not be interpreted as a current market quotation.

Operating cost included delivered ore, beneficiation, net NaOH make-up, power and fuel, water and minor reagents, labour, maintenance, residue management, administration and quality control. Net present value, internal rate of return, simple payback and the minimum selling price at zero NPV were calculated. Sensitivity tests varied product price, recovery, reagent cost, capital cost, energy cost and plant availability.

$$NPV = -I_0 + \Sigma [CF⍰/(1 + r)^t] \quad (5)$$

$$MSP: NPV(P = MSP) = 0 \quad (6)$$

5.6 Environmental Assessment

Environmental assessment followed a cradle-to-gate screening structure with one tonne of lithium carbonate as the functional unit. The categories were climate-change potential, cumulative energy demand, freshwater withdrawal, acidification and solid process residue. Background burdens were assigned to electricity, natural gas, NaOH, lime, soda ash and transport using literature ranges reported for hard-rock lithium supply (Chordia et al., 2022). The conventional sulfuric-acid route was normalized to an index of 100, while the integrated route was evaluated under grid/gas and hybrid-renewable energy scenarios.

The analysis emphasized hotspot identification rather than a false claim of full ISO-compliant life-cycle assessment. Nigerian grid composition, generator use, reagent origin, transport distance and water scarcity are site-specific and must be replaced with measured inventories. Social risks—land acquisition, informal mining, worker safety and community benefit sharing—were discussed qualitatively because they cannot be represented adequately by the five environmental indicators alone.

6.0 RESULTS AND DISCUSSION

6.1 Optimization Response and Operating Window

The response surface showed that temperature and NaOH ratio had stronger effects than residence time within the selected range. Recovery rose rapidly as the temperature approached the NaOH melting region, then levelled because the accessible spodumene surface had largely reacted. Excess caustic improved conversion but imposed a direct cost and enlarged the sodium inventory that had to be recovered. The sustainability-weighted optimum was 333 °C, a NaOH-to-spodumene ratio of 1.47 and 83 min, giving a predicted lithium extraction of 97.5%. The maximum-recovery region was slightly hotter and more reagent-intensive, but the difference in extraction was less than one percentage point.

The result supports the central process argument: the best operating point is not necessarily the point with the highest laboratory recovery. At commercial scale, a 0.5% gain in extraction may be outweighed by additional caustic purchase, washing water, evaporative duty and maintenance. Conversely, operating too close to the lower boundary would increase unreacted lithium in the residue and could make residue utilization more difficult. A practical control window of 325–340 °C, ratio 1.40–1.58 and 70–90 min is therefore proposed for pilot work. Feed mineralogy should be included as a fourth factor because mica-rich or petalite-rich blends may respond differently from coarse spodumene concentrate.

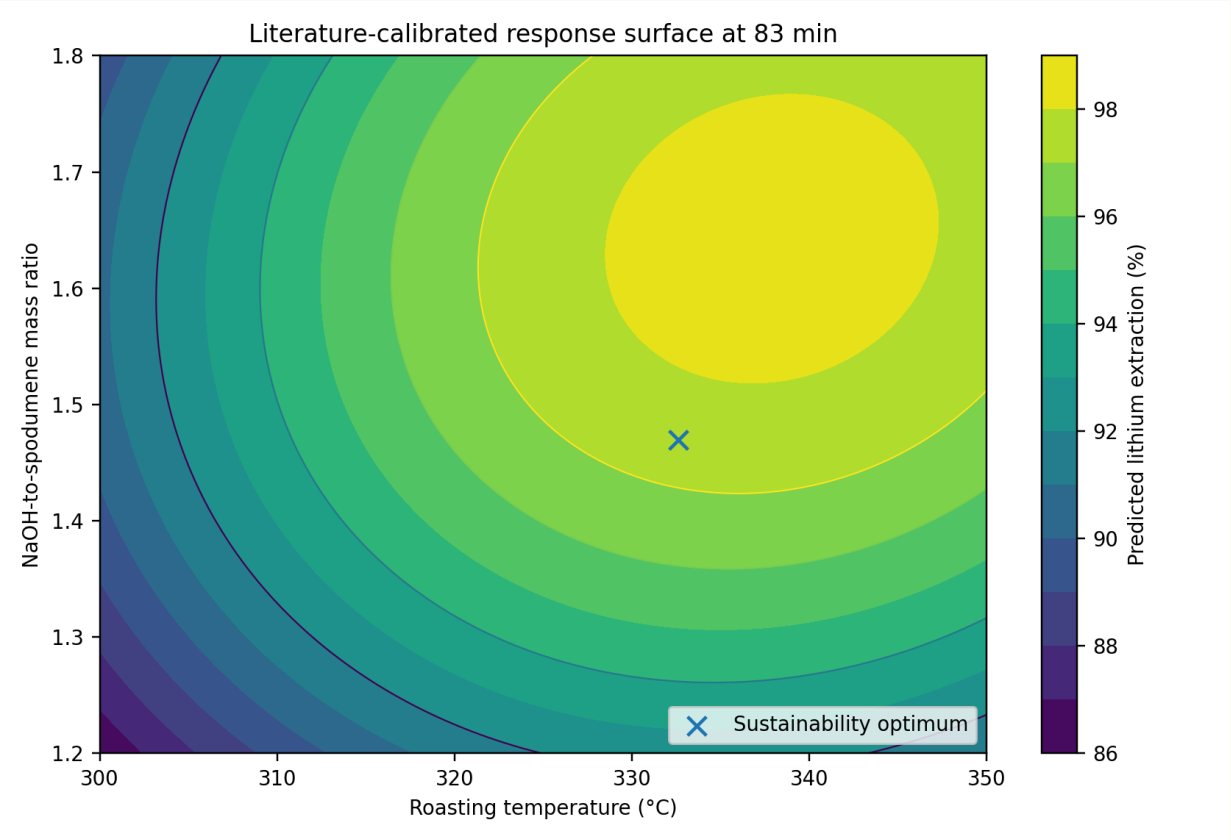

Figure 4. Predicted Lithium Extraction as a Function of Roasting Temperature and NaOH Dosage

Table 3. Optimization Results and Proposed Pilot Operating Window

Item	Temperature (°C)	NaOH/spodumene	Time (min)	Li extraction (%)
Low-severity point	315	1.35	60	92.6
Centre point	325	1.50	75	96.9
Sustainability optimum	333	1.47	83	97.5
High-recovery point	335	1.65	90	98.5
Recommended pilot window	325–340	1.40–1.58	70–90	96–98.5 target

6.2 Integrated mass balance and lithium yield

For one tonne of ore at 1.08% Li_2O, the model contained 10.8 kg Li_2O. Combined DMS and middlings flotation recovered 89.5% of that lithium into approximately 176 kg of 5.5% Li_2O concentrate. Direct roasting and water leaching transferred 97.2% of concentrated lithium to solution, and purification–precipitation recovered 96% of dissolved lithium as lithium carbonate. The resulting product yield was 22.3 kg Li_2CO_3 per tonne of ore, corresponding to an overall lithium recovery of 83.5%.

The value of coarse waste rejection is evident from the thermal balance. Without beneficiation, one tonne of raw ore would require heating and chemical contact. In the integrated circuit, less than one-fifth of the original mass enters the roaster. The energy saving is not proportional only to mass, because moisture, heat

losses and reactor loading also matter, but pre-concentration remains the most powerful early intervention. It also isolates a relatively clean gangue stream before caustic treatment. This supports the sequence proposed by Wang et al. (2025), where dense-medium separation is used not merely to make a concentrate but to reshape the economics of the downstream refinery.

The principal uncertainty is the behaviour of the middlings flotation product. Fine mica and feldspar can consume reagents, dilute the combined concentrate and introduce potassium, sodium, iron or fluorine into the leach circuit. The plant should therefore retain the ability to stockpile or separately treat difficult middlings rather than forcing all material through one blend. A geometallurgical model linking ore domain, DMS yield, flotation response and direct-roast recovery would be more valuable than a single annual-average grade.

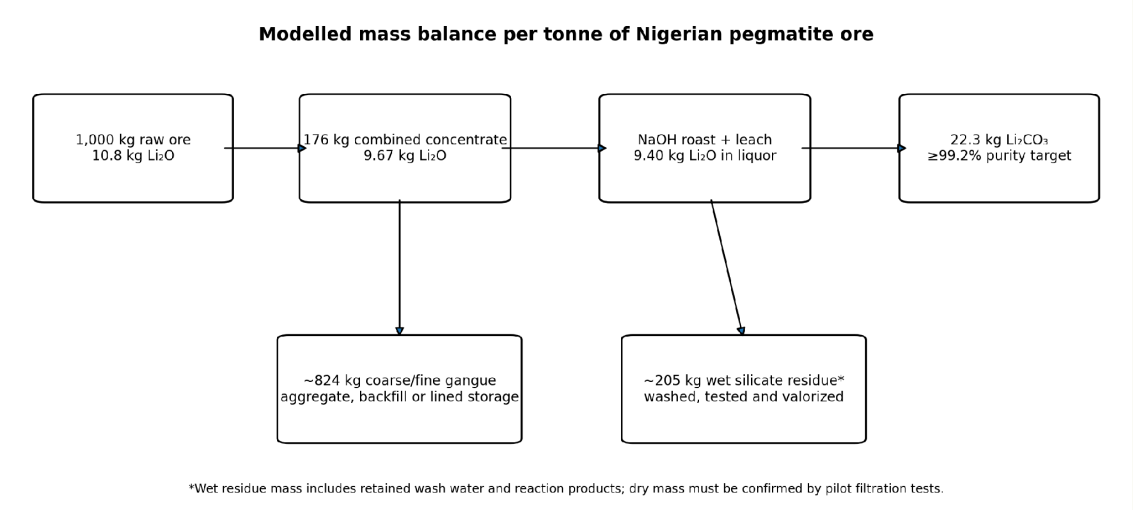

Figure 5: Modelled Mass Balance and Principal Residue Streams Per Tonne of Ore

Table 4: Base-case Mass and Utility Inventory Per Tonne of Ore

Stream or utility	Quantity	Report
Combined spodumene concentrate	176 kg	5.5% Li_2O; includes middlings flotation recovery
Lithium carbonate product	22.3 kg	96% precipitation recovery; ≥99.2% purity target
Net NaOH make-up	46 kg	Assumes approximately 70% effective caustic recovery
Freshwater make-up	0.60 m^3	Assumes 75% water recycle and controlled bleed
Electricity	95 kWh	Crushing, DMS, grinding, pumping, filtration and finishing
Low-temperature process heat	0.35 GJ	Roasting duty after heat recovery; site verification required
Coarse/fine gangue reject	~824 kg	Characterize for aggregate, backfill or engineered storage

Wet extraction residue	~205 kg	Dry-solids and leachability to be established by pilot filtration

6.3 Economic performance

At 200,000 t ore per year, annual lithium-carbonate output was approximately 4,461 t. Total installed capital was estimated at US$98.2 million. The roasting–leaching–purification area accounted for the largest share because it requires corrosion-resistant equipment, solid–liquid separation, heat recovery and reagent-recycle systems. Beneficiation capital was smaller but essential; removing gangue before chemical treatment reduced the required refinery capacity and improved the capital efficiency of every downstream unit.

Annual operating cost was US$28.8 million, equivalent to about US$6,456 per tonne of lithium carbonate. Delivered ore and net caustic make-up were the two largest cost items. This result explains why resource grade and reagent recycling must be evaluated together. A lower-grade ore can still be viable when coarse rejection is effective, while a high laboratory extraction can become uneconomic if fresh NaOH is effectively consumed once. At the assumed product price of US$14,000 t^{-1}, annual revenue was US$62.5 million and EBITDA was US$33.7 million.

The discounted model returned an NPV of US$80.7 million, an IRR of 22.9% and a simple payback of 4.2 years. The minimum selling price at zero NPV was approximately US$10,602 t^{-1}. These figures indicate a potentially attractive project, but they should be read as a screening result. Capital estimates for Nigerian chemical plants can be affected by imported equipment, foreign-exchange movement, port delay, spare-parts inventory and the cost of captive power. A bankable estimate requires vendor quotations, local construction factors, tax incentives, royalties, working capital and a detailed ramp-up schedule.

Table 5: Screening Capital Estimate

Area	Installed cost (US$ million)	Share (%)
Crushing, screening and DMS	14.0	14.3
Grinding and flotation	12.5	12.7
NaOH roasting and heat recovery	26.0	26.5
Leaching, purification and carbonation	18.0	18.3
Water, effluent and residue systems	8.5	8.7
Utilities, storage, laboratory and buildings	6.0	6.1
Engineering, owner’s cost and contingency	13.2	13.4
Total installed capital	98.2	100.0

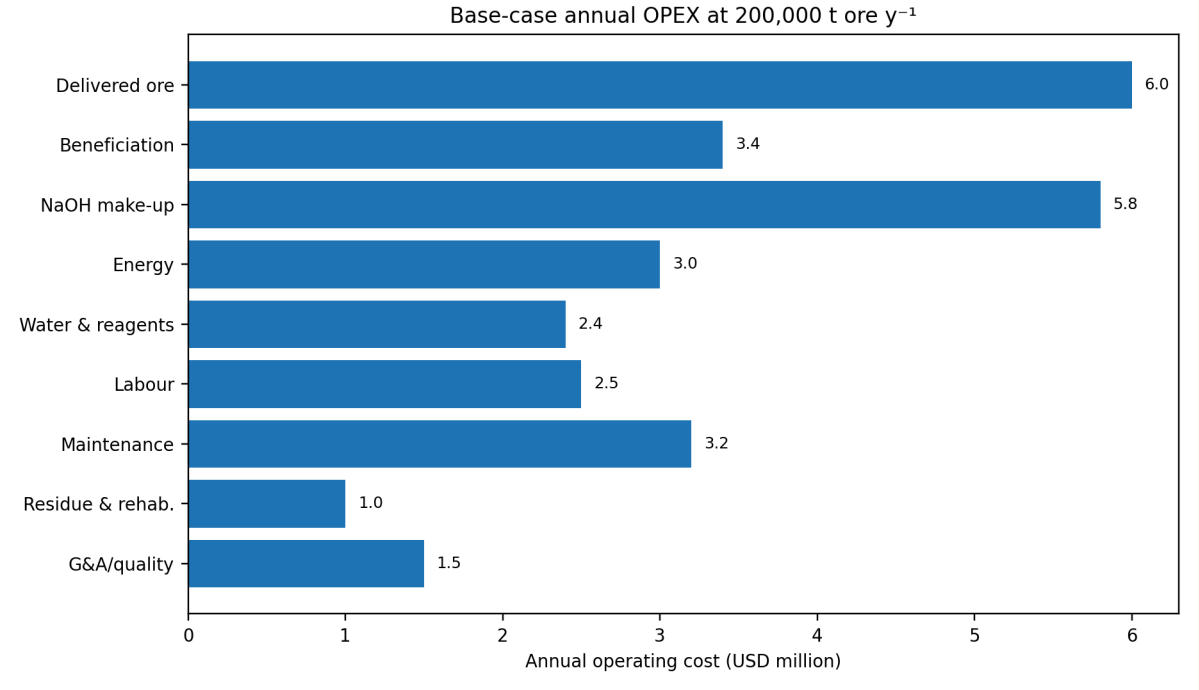

Figure 6: Base-case Annual Operating-cost Distribution.

Table 6. Base-case Techno-economic Indicators

Indicator	Value
Ore throughput	200,000 t y^{-1}
Lithium carbonate production	4,461 t y^{-1}
Product price scenario	US$14,000 t^{-1}
Annual operating cost	US$28.8 million
Unit operating cost	US$6,456 t^{-1} Li_2CO_3
Total installed capital	US$98.2 million
NPV at 10%	US$80.7 million
Internal rate of return	22.9%
Simple payback	4.2 years
Minimum selling price	US$10,602 t^{-1} Li_2CO_3

6.4 Sensitivity and Commercial Risk

Product price produced the widest NPV range, followed by overall lithium recovery and total installed capital. That ordering is typical for lithium projects because revenue depends on both a volatile chemical price and a chain of recoveries from ore sorting to final precipitation. The sensitivity result also confirms that the project should not be designed around a single spot-price year. Offtake agreements may reduce price exposure, but they can also impose strict impurity limits, qualification periods and penalties that should be incorporated in the financial model.

Recovery sensitivity is more operationally useful because it can be managed. A two-percentage-point loss at DMS, flotation, leaching and precipitation compounds across the circuit. Online density control, feed blending, rapid mineralogy, lithium assays on residue and disciplined wash-water accounting are therefore revenue-control measures, not merely laboratory activities. Similarly, the NaOH recycle rate should be treated as a key performance indicator. The financial model assumes a net make-up of 46 kg per tonne of ore; sustained consumption above that level would increase cost and enlarge the environmental footprint of caustic manufacture.

Plant availability is another Nigerian-specific risk. The process contains several continuous solid–liquid and thermal operations that do not tolerate frequent power interruption. A hybrid power system with grid connection, gas or biogas backup, solar photovoltaic generation and thermal storage is more robust than dependence on diesel generators. The economic benefit is not limited to energy price. Stable power improves filtration, prevents precipitation in lines, protects refractory and avoids off-specification product during restarts.

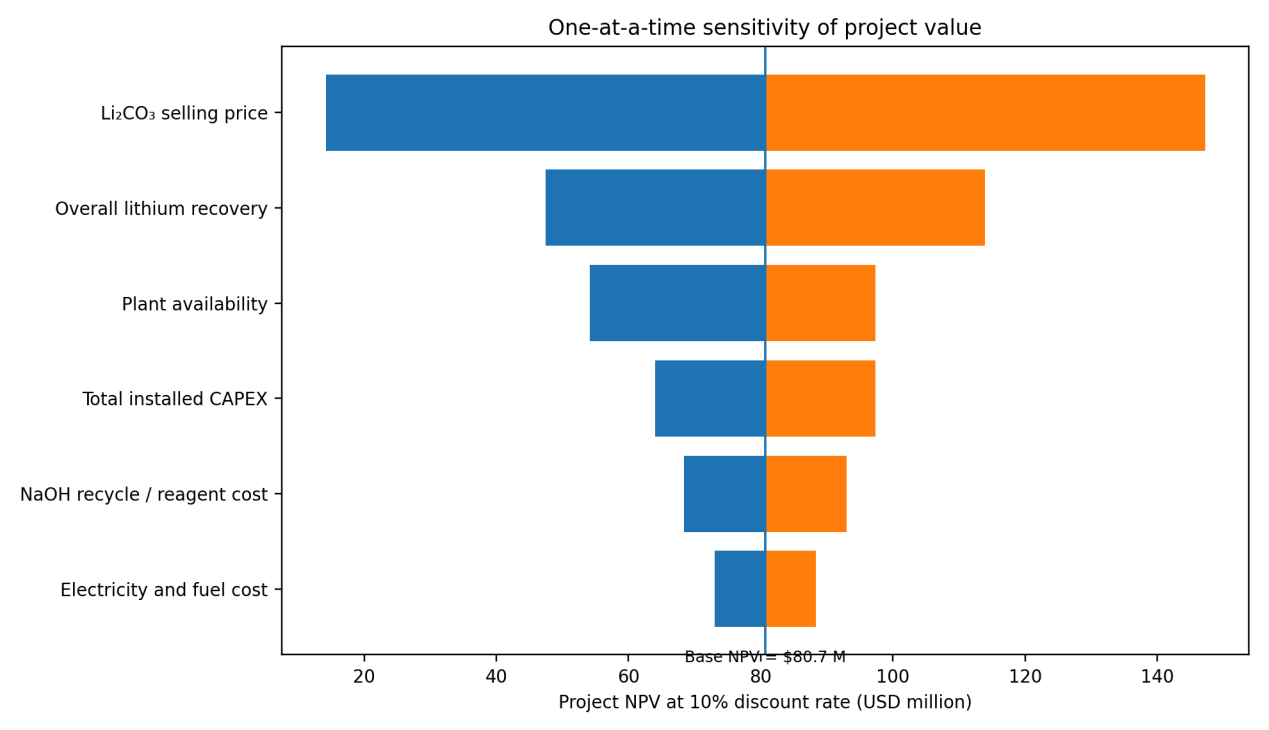

Figure 7: One-at-a-time Sensitivity of Net Present Value.

6.5 Environmental Performance And Circularity

The integrated route had a lower impact profile than the conventional acid benchmark in every screened category. Under grid- and gas-dominant energy, climate impact fell to an index of 72; under the hybrid-renewable scenario it fell to 46. The direction and scale are consistent with the central result of Sharifian et al. (2026), who found that low-temperature direct processing substantially reduced global-warming potential relative to conventional calcination and acid baking. The benefit came from avoiding the 1,100 °C phase-conversion kiln, reducing acid production and neutralization, and treating a pre-concentrated rather than raw ore stream.

The energy source remained decisive. A low-temperature process operated with inefficient diesel generation could surrender much of its advantage. Heat recovery, insulated reactors, solar electricity, efficient motors and scheduling of high-load grinding operations are therefore part of the metallurgical flowsheet. The model's hybrid scenario also assumes that process water is recycled and that

lithium-bearing mother liquor is returned rather than discharged. Freshwater withdrawal was estimated to fall by about 39% relative to the conventional benchmark. In water-stressed communities, however, a volumetric reduction alone is insufficient; the plant must assess seasonal availability, competing users and downstream water quality.

Residue circularity produced a meaningful but conditional improvement. The DMS reject is the largest solid stream and has the best reuse potential because it is coarse and chemically unaltered. It may be suitable for road base, aggregate or backfill after petrographic, strength and leachability tests. The alkaline extraction residue is more complex. Wang et al. (2021) demonstrated that spodumene waste can be transformed into useful silicate minerals, while Mowbray et al. (2026) showed a broader near-zero-waste strategy with alumina and silica co-products. A Nigerian plant should begin with modest, verified uses rather than assign full product credit in the base case. Until a buyer, specification and long-term liability arrangement exist, the material remains a residue in the economic model.

The process also has local social and governance implications. Formal value addition can create skilled employment and strengthen traceability, but it does not automatically correct unsafe or informal mining. Feed acceptance should require licensed origin, chain-of-custody records, prohibition of child labour, occupational exposure controls and community grievance procedures. These requirements should be audited alongside product chemistry. Sustainable lithium cannot be defined only by carbon intensity when the ore enters the plant through an opaque or abusive supply chain.

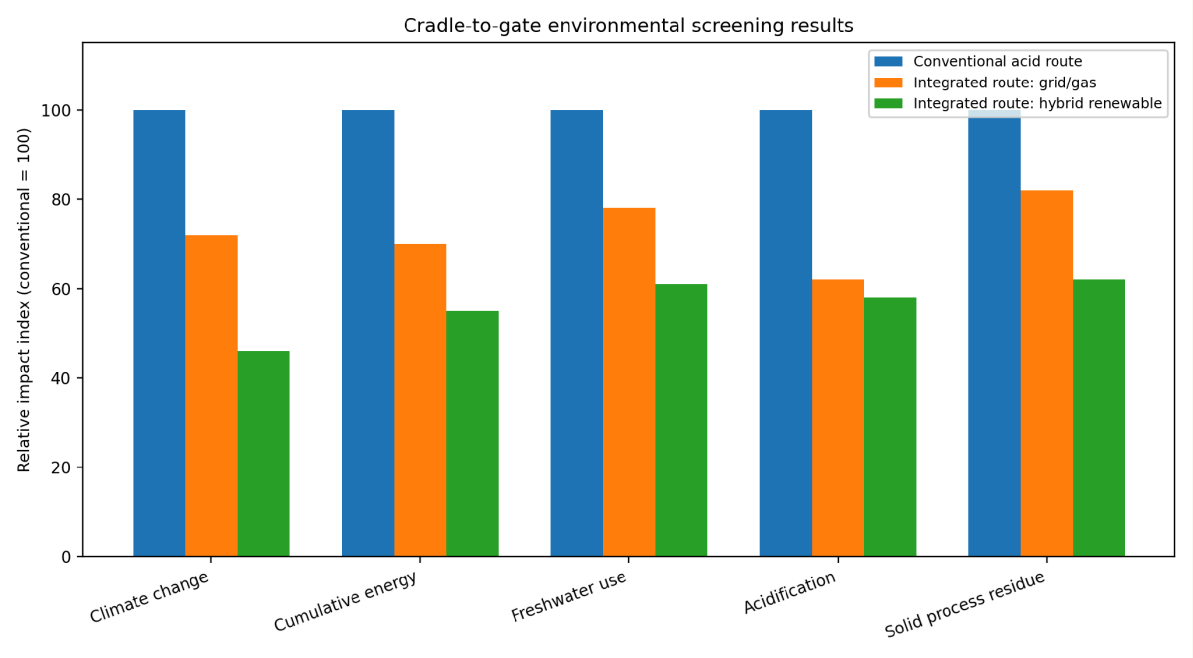

Figure 8: Relative Cradle-to-gate Environmental Screening for the Conventional and Integrated Routes.

Table 7: Environmental Inventory and Hotspot Interpretation

Indicator	Conventional benchmark	Integrated grid/gas	Integrated hybrid	Dominant hotspot
Climate change	6.7 t CO_2-e/t Li_2CO_3	4.8 t CO_2-e	3.1 t CO_2-e	Electricity, heat and NaOH manufacture

Cumulative energy	100 index	70	55	Roasting, grinding and reagent production
Freshwater withdrawal	29 m^3/t Li_2CO_3	23 m^3	18 m^3	Washing, cooling and purge control
Acidification	100 index	62	58	Acid/alkali production and combustion emissions
Solid process residue	100 index	82	62	Extent of gangue rejection and verified reuse

6.6 Comparison With Recent Process-Development Studies

The proposed route sits between established industrial practice and emerging near-zero-waste concepts. It is less radical than the ammonium-fluoride process reported by Mowbray et al. (2026), which operates below 100 °C and co-produces alumina and silica, but the NaOH route has a clearer progression of published reagent screening, optimization and TEA–LCA evidence (Han et al., 2022; Sharifian et al., 2026; Subasinghe & Rezaee, 2025). It also avoids the chloride off-gas and high-temperature corrosion issues associated with dry chlorination (Fosu et al., 2022).

Compared with composite-salt roasting, the selected route uses a lower temperature but a more aggressive reagent. Ni et al. (2025) reported 95.45% lithium leaching at 900 °C using Na_2SO_4–CaO, while Jiang et al. (2024) obtained 95.9% from lepidolite at 775 °C using microwave-enhanced sulfate roasting. These alternatives may become preferable when Nigerian feed contains a higher proportion of lepidolite or when caustic recovery proves difficult. The process-development programme should therefore preserve optionality: concentrate mineralogy should determine the campaign route, and a single national flowsheet should not be imposed on every pegmatite deposit.

The principal contribution of this study is the linkage between Nigerian beneficiation evidence and a direct-extraction refinery model. Previous publications demonstrate individual technologies; the present framework shows how coarse waste rejection, middlings recovery, low-temperature conversion, water recycle, economic uncertainty and residue responsibility affect one another. That system's view is necessary for project selection because a technically impressive leach test can still fail when placed inside an uneconomic or environmentally weak plant.

6.7 Limitations and Uncertainty

The analysis is intentionally transparent about the difference between process-development evidence and bankable project data. The mineral grade used in the model is grounded in a published Nigerian beneficiation study, while most refinery parameters were calibrated from recent international experiments. Ore texture, accessory minerals, weathering, grindability and impurity deportment may differ materially among Nigerian pegmatites. A change in mica content, for example, can increase fine-particle losses, alter flotation selectivity and raise potassium, iron or aluminium loading in the purification circuit. The flowsheet should therefore be treated as a testable design hypothesis rather than a universal recipe for every deposit.

Economic estimates carry a similar limitation. The capital model is a Class 4-type screening estimate

assembled from factored equipment costs, assumed Nigerian installation conditions and a defined production scale. It does not include a completed resource model, detailed mine schedule, firm engineering quotations, financing structure or negotiated product specification. Exchange-rate movements, imported-equipment lead times, road upgrades, captive power, security arrangements and working-capital requirements could change the investment case. The positive base-case NPV is consequently useful for identifying the variables that deserve attention, not as a substitute for a feasibility study.

Environmental results are comparative indicators rather than a site-specific impact assessment. The inventory does not replace seasonal baseline monitoring of groundwater, surface water, biodiversity, dust, noise, traffic and community livelihoods. Likewise, residue valorization was credited only in the improvement scenario and should remain conditional on leachability, durability, market demand and regulatory acceptance. Future work should integrate pilot measurements with uncertainty propagation, spatial water-stress data and Nigerian electricity scenarios. Reporting confidence intervals around recovery, reagent use, emissions and cost will be more informative than presenting a single deterministic value with false precision.

6.8 Nigerian Pilot and Scale-Up Framework

A staged programme is recommended before committing to a commercial refinery. Stage 1 should establish geometallurgical variability using composites from at least the major lithological and weathering domains. Each composite should be tested for size-by-assay, DMS response, flotation response, direct-roast recovery, impurity dissolution and residue filtration. The outcome should be a domain model that predicts concentrate grade, recovery and reagent consumption over the mine schedule.

Stage 2 should operate a continuous demonstration circuit. A suitable target is 0.5–1.0 t concentrate per day, large enough to test feed mixing, heat transfer, two-stage roasting, counter-current washing, caustic recovery, scale formation and product purity. Batch tests often overstate performance because they use ideal mixing and fresh water. Continuous work should include planned recycle build-up and a long campaign that reveals sodium, aluminium, silica and potassium accumulation.

Stage 3 should qualify product and residues. Lithium carbonate samples should be sent to independent laboratories and prospective customers. Coarse gangue and washed residue should undergo geotechnical, durability and leachability testing under Nigerian rainfall conditions. A residue product should enter the financial model only after a technical specification, market volume and liability allocation are defined. Stage 4 should update the TEA and LCA with vendor quotations, metered energy, reagent consumption and actual transport routes. The decision gate should compare at least the selected NaOH route, a sulfate-roast alternative and the option of selling concentrate rather than refining it domestically.

Institutional coordination is equally important. Geological data, mine licensing, environmental approval, water allocation, power supply, product standards and export policy fall under different agencies. A credible project will need a single data room containing resource models, metallurgical results, chain-of-custody evidence, environmental baseline, community agreements and financial assumptions. This level of transparency is more likely to attract patient capital than promotional claims about ore grade without process evidence.

Table 8: Priority Pilot Tests and Decision Criteria

Work package	Minimum evidence	Decision criterion
Ore variability	Multi-domain composites and size-by-assay	No domain causes unacceptable recovery or reagent spikes

Beneficiation	Continuous DMS and locked-cycle flotation	Combined recovery ≥87%; concentrate ≥5.2% Li_2O
Direct roasting	Continuous two-stage operation	Extraction ≥95%; stable temperature and corrosion control
Recycle circuit	Water and caustic accumulation test	Net NaOH make-up ≤55 kg/t ore; no uncontrolled scaling
Product quality	Independent chemical qualification	Li_2CO_3 ≥99.2% and impurity limits accepted by buyer
Residue safety	Mineralogy, pH, leachability and durability	Compliant reuse route or engineered storage design
Economics	Vendor-based estimate and Nigerian cost factors	Positive NPV under downside price/recovery case
ESG and traceability	Licensed supply, labour audit, community plan	No untraceable or abusive feed accepted

7.0 CONCLUSIONS AND RECOMMENDATIONS

This study shows that a sustainable Nigerian lithium project should be designed as an integrated mineral-processing and chemical system. For a representative 1.08% Li_2O pegmatite, coarse dense-medium separation followed by flotation of middlings reduces the mass entering the refinery and supports a combined lithium recovery near 89.5%. Low-temperature NaOH roasting and water leaching then offer a credible alternative to the conventional high-temperature sulfuric-acid route. The literature-calibrated optimum was approximately 333 °C, a NaOH-to-spodumene ratio of 1.47 and 83 min, with predicted extraction close to 97.5%.

At the selected scale, the model produced about 4,460 t y^{-1} lithium carbonate, a unit operating cost near US$6,460 t^{-1} and a positive investment case at the stated price assumptions. The environmental advantage was strongest when low-temperature processing was combined with renewable electricity, heat recovery, water recycle and verified use of coarse gangue and silicate residue. The analysis also identified the major vulnerabilities: lithium price, compounded recovery losses, caustic recycle, capital escalation, plant availability and the social legitimacy of the ore supply.

The immediate recommendation is not full-scale construction. Nigeria should first support a continuous pilot programme based on representative ore domains, closed-loop recycle, independent product qualification and residue testing. The process should be advanced only when the pilot confirms lithium recovery, net reagent consumption, corrosion behaviour, water balance and product purity. Such evidence would convert Nigeria's geological opportunity into a defensible value-addition project while avoiding the cost and environmental legacy of prematurely scaling an unverified flowsheet.

References

Asif, A. H., Li, C., Lim, H., & Sun, H. (2024). Australia's spodumene: Advances in lithium extraction technologies, decarbonization, and circular economy. *Industrial & Engineering Chemistry Research*, *63*(5), 2073–2086. https://doi.org/10.1021/acs.iecr.3c04048

Chordia, M., Wickerts, S., Nordelöf, A., & Arvidsson, R. (2022). Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene. Resources, Conservation and Recycling, 187, 106634. https://doi.org/10.1016/j.resconrec.2022.106634

Fosu, A. Y., Kanari, N., Bartier, D., Vaughan, J., & Chagnes, A. (2022). Novel extraction route of lithium from alpha-spodumene by dry chlorination. *RSC Advances*, *12*(33), 21468–21481. https://doi.org/10.1039/D2RA03233C

Han, S., Sagzhanov, D., Pan, J., Vaziri Hassas, B., Rezaee, M., Akbari, H., & Mensah-Biney, R. (2022). Direct extraction of lithium from α-spodumene by salt roasting–leaching process. *ACS Sustainable Chemistry & Engineering*, *10*(40), 13495–13504. https://doi.org/10.1021/acssuschemeng.2c04402

Han, S., Sagzhanov, D., Pan, J., Vaziri Hassas, B., Rezaee, M., Akbari, H., and Mensah-Biney, R. (2022). Direct extraction of lithium from α-spodumene by salt roasting–leaching process. *ACS Sustainable Chemistry & Engineering, 10*(40), 13495–13504. doi:10.1021/acssuschemeng.2c04402.

Ibsaine, F., Dionne, J., Tran, L. H., Coudert, L., Pasquier, L.-C., and Blais, J.-F. (2024). Scaling up, mass balance and techno-economic study of a hydrothermal process used to synthesize zeolite from aluminosilicate residues obtained from lithium production. *Minerals Engineering, 216*, 108841. doi:10.1016/j.mineng.2024.108841.

International Energy Agency. (2025). Global critical minerals outlook 2025. IEA.

Jiang, M., Liu, J., Fu, L., Zuo, Y., Zhang, G., Wang, S., & Zhang, L. (2024). Microwave-enhanced sulfate roasting for lithium extraction from lepidolite: A comprehensive study. *Journal of Cleaner Production*, *434*, 140248. https://doi.org/10.1016/j.jclepro.2023.140248

Kundu, T., Rath, S. S., Das, S. K., Parhi, P. K., & Angadi, S. I. (2023). Recovery of lithium from spodumene-bearing pegmatites: A comprehensive review on geological reserves, beneficiation, and extraction. *Powder Technology*, *415*, 118142. https://doi.org/10.1016/j.powtec.2022.118142

Mowbray, B. A. W., Hunt, C., Fuelling, K. M., Prawira, J., Jafari, K., Strong, N., & Chiang, Y.-M. (2026). Valorization of lithium hardrock concentrates into battery raw materials and commodity products. *Science*, *392*(6801), 980–984. https://doi.org/10.1126/science.aec4652

Ni, C., Liu, C., Wang, J., Song, Y., Liang, Y., Xie, W., Zhong, H., & He, Z. (2025). Highly efficient lithium leaching from alpha-spodumene via binary composite salts low-temperature roasting process. *Powder Technology*, *449*, 120404. https://doi.org/10.1016/j.powtec.2024.120404

Pimassoni, Y., Ramesh, Y., Zeng, F., & Granata, G. (2025). Direct extraction of lithium from alpha-spodumene by alkali mechanochemical conversion and water leaching. *Chemical Engineering and Processing – Process Intensification*, *216*, 110438. https://doi.org/10.1016/j.cep.2025.110438

Rezaee, M., Han, S., Sagzhanov, D., Vaziri Hassas, B., Slawecki, T. M., Agrawal, D., Akbari, H., & Mensah-Biney, R. (2022). Microwave-assisted calcination of spodumene for efficient, low-cost and environmentally friendly extraction of lithium. *Powder Technology*, *397*, 116992. https://doi.org/10.1016/j.powtec.2021.11.036

Rioyo, J., Tuset, S., & Grau, R. (2022). Lithium extraction from spodumene by the traditional sulfuric acid process: A review. *Mineral Processing and Extractive Metallurgy Review*, *43*(1), 97–106. https://doi.org/10.1080/08827508.2020.1798234

Roy, T., Plante, B., Benzaazoua, M., and Demers, I. (2023). Geochemistry and mineralogy of a spodumene-pegmatite lithium ore at various mineral beneficiation stages. *Minerals Engineering, 202*, 108312. doi:10.1016/j.mineng.2023.108312.

Sharifian, S., Nikfar, S., Subasinghe, C., Iranmanesh, Z., Rezaee, M., & Vahidi, E. (2026). Conventional vs. direct vs. electrochemical lithium extraction: A holistic TEA–LCA of lithium carbonate production from spodumene. *Green Chemistry*, *28*(2), 1144–1157. https://doi.org/10.1039/D5GC04866D

Sharifian, S., Nikfar, S., Subasinghe, C., Iranmanesh, Z., Rezaee, M., and Vahidi, E. (2026). Conventional vs. direct vs. electrochemical lithium extraction: A holistic TEA–LCA of lithium carbonate production from spodumene. *Green Chemistry, 28*(2), 1144–1157. doi:10.1039/D5GC04866D.

Subasinghe, H. C. S., & Rezaee, M. (2025). Direct lithium extraction from α-spodumene using NaOH roasting and water leaching. *Chemical Engineering Journal*, *505*, 159661. https://doi.org/10.1016/j.cej.2025.159661

Subasinghe, H. C. S., and Rezaee, M. (2025). Direct lithium extraction from α-spodumene using NaOH roasting and water leaching. *Chemical Engineering Journal, 505*, 159661. doi:10.1016/j.cej.2025.159661.

U.S. Geological Survey. (2025). Mineral commodity summaries 2025. https://doi.org/10.3133/mcs2025

Wang, S., Wang, J., Qiu, G., Shen, L., Liao, R., & Wu, L. (2025). Computational and experimental research on dense medium separation of low-grade spodumene. *Minerals*, *15*(5), 434. https://doi.org/10.3390/min15050434

Wang, S., Wang, J., Qiu, G., Shen, L., Liao, R., and Wu, L. (2025). Computational and experimental research on dense medium separation of low-grade spodumene. *Minerals, 15*(5), 434. doi:10.3390/min15050434.

Wang, X., Hu, H., Liu, M., Li, Y., Tang, Y., Zhuang, L., & Tian, B. (2021). Comprehensive utilization of waste residue from lithium extraction process of spodumene. *Minerals Engineering*, *170*, 106986. https://doi.org/10.1016/j.mineng.2021.106986

Zhang, Y., Ma, B., Lv, Y., Wang, C., & Chen, Y. (2023). An effective method for directly extracting lithium from α-spodumene by activated roasting and sulfuric acid leaching. *Journal of Industrial and Engineering Chemistry*, *122*, 540–550. https://doi.org/10.1016/j.jiec.2023.03.017