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REVIEW

Sustainable Utilization of Lithium in Alumina-Rich Ores: Insights from Geology, Processing, and Environmental Management

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ABSTRACT

Clay-hosted and altered aluminosilicate lithium ores, often rich in alumina, are becoming significant additions to conventional brine and spodumene supply. Their sustainable development hinges on recognizing linked mineralogical and processing constraints. Lithium is typically concentrated in fine-grained aluminosilicate hosts, and extraction conditions that liberate lithium can also mobilize large amounts of aluminium and silica. This drives high reagent consumption, silica gelation, inefficient solid-liquid separation, complex impurity deportment, and voluminous residues. The review synthesizes a geometallurgy-led framework that links deposit setting, lithium deportment, texture, reactivity indices, and impurity suites to select suitable processing routes and manage environmental impacts. It compares major flowsheet families: direct leaching, thermal activation followed by aqueous leaching; alkaline and hybrid strategies; and emerging selective separations, highlighting domain-specific trade-offs among recovery, operability, reagent intensity, energy demand, water recycle, and residue risk. Across routes, aluminium and silica behaviour is the dominant control on plant performance and sustainability hotspots, especially under steady-state recycle water chemistry, where salt deposition can alter rheology and precipitation equilibria. The authors propose domain-sensitive decision logic and a minimum reporting database to improve comparability across studies, and recommend integrating techno-economic analysis and life-cycle assessment with ore variability. Priority research areas include highly selective lithium separation with minimal aluminosilicate dissolution, low-carbon heat for activation, robust closed-loop water/salt management and stabilization, and viable residue valorization and long-term closure pathways. These advances should be paired with impurity monitoring, control, and governance.

Keywords: Alumina-Rich Ores; Lithium Deportment; Geometallurgy; Processing Routes; Sustainability

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1. Introduction

Lithium is now a strategic energy transition raw material, the foundation of the fast-paced expansion of rechargeable batteries in electric vehicles, grid-scale storage, and portable electronics [1]. Alongside the increase in demand, the lithium supply chain is under increasing environmental performance pressure, as well as water consumption, land disturbance, chemical intensity, and long-term risks of residue and tailings storage [2]. These demands are redefining the appearance of successful lithium production: elevated recycling and product quality are no longer sufficient factors in themselves, and future ventures are now being evaluated based on how well they can address high sustainability standards and still be economically viable. In this background, new sources of non-traditional lithium ores, particularly those containing alumina, are being reconsidered as substitutes for the traditional sources of lithium, the brine and hard-rock spodumene ores [3].

Lithium ores with significant alumina content. Lithium ores containing aluminum-bearing material are, in general, those in which the gangue is dominated by aluminum-bearing phases, and which may contain a significant proportion of lithium. The categories of materials that include lithium deposits that are clay-hosted (e.g., smectite-, illite-, and mixed-layer clay systems), lateritic or bauxitic associations, in which lithium may exist in fine-grained aluminosilicates, and altered volcanic or sedimentary materials, enriched in Li due to weathering, diagenesis, or hydrothermal treatments [4]. Although the mineral assemblages are not the same, these ores have many characteristics of processing interest: (i) lithium may be structurally bound in the aluminosilicate lattices as opposed to existing in the form of discrete, readily liberated minerals; (ii) the feed can be small grained and tends to form slimes, making handling of solids and solid liquid separation difficult; and (iii) high reactivity of aluminum and silica can lead to excessive use of reagents, development of gel, scaling, and large volumes of chemically complex residues. These characteristics form an opportunity and a limitation. On the one hand, alumina-rich ores are able to increase the resource base, as well as diversify the geography of supply. On the other hand, they put downstream pressure on traditional flowsheets and may have a sustainability cost to them should they be approached with a form of brute force chemistry that dissolves large gangue quantities.

The most apparent opposition is to the two overwhelming paradigms of production. Depending on water balance, brine chemistry, and local hydrology, the operations of brine are usually based on solar evaporation and/or direct lithium extraction (DLE) [5,6]. The operations of hard-rock spodumene, in contrast, are energy-intensive because of the high-temperature conversion stages and can attain relatively mature and predictable performance at scale. The third place is occupied by alumina-rich ores: they might not have to deal with certain brine-related water conflicts or certain hard-rock mining limitations, but they bring their own technical and environmental issues of high gangue dissolution, impurity management, and residue disposal. Notably, bulk grade does not control the performance of these ores. Even two ores of similar lithium grades can respond quite differently to comminution, leaching, filtration, purification, and the stability of the residue, determined by the identity of Li host phases, the presence of reactive alumina/silica, the extent of weathering or diagenesis, and impurities being carbonates, magnesium, calcium, fluorine, chloride, and sulfate. This fluctuation has an important implication on the manner in which projects are to be assessed and contrasted, and it inspires the process of reviewing ore characteristics as the core of processes and sustainability decisions.

Mismatch between clay and aluminosilicate-based systems, the incompatibility of mineralogical reality and flowsheet design, is a consistent cause of underperformance in systems rich in clay and aluminosilicate [7]. The traditional methods tend to consider that increased chemical intensity, stronger acid, increased temperature, and increased residence time will be consistently translated into increased lithium recovery. In alumina-enriched ores, this equilibrium is often not true due to the ability of the additional effort to dissolve aluminum and silica in disproportionation and raise the acid cost, resulting in gelatinous silica layers that disrupt mixing, solid-liquid separation, and further upgrading. The resultant process can achieve acceptable recoveries of lithium in lab experiments but be impractical at the scale level due to corrosion, neutralization requirements, water recycle difficulties, and because it produces large quantities of salt-containing byproducts.

In these instances, it is not the lithium reaction that is the limiting factor, but the behavior of the gangue matrix and impurities as a whole and throughout the entire circuit. The only answer to this is that single-stage optimization (e.g., maximization of leach extraction) should be replaced with system-level optimization, where the mineralogy, the texture, and geochemistry of the ore dictate the choice of route, impurity control, water and reagent recycling, and the residue management at the start of the process.

In this review, "alumina-rich lithium ores" is used as an operational term for lithium-bearing, non-brine ore systems in which Al-bearing clay or aluminosilicate phases are either major lithium hosts or major reactive gangue phases controlling extraction and environmental performance. Indicatively, these ores may show elevated bulk Al_2O_3 contents, for example, >15 wt.% Al_2O_3, or contain abundant reactive Al-Si phases such as smectite, illite, mixed-layer clays, mica-derived phases, altered feldspar/mica assemblages, or bauxitic/lateritic aluminosilicate materials. However, classification is not based on bulk Al_2O_3 alone; lithium deportment, reactive aluminosilicate abundance, silica/aluminium dissolution behavior, fines content, and impurity suites are treated as the decisive criteria. This requirement is very much in line with the concept of geometallurgy. Geometallurgy is a synergy of geological knowledge with quantitative mineralogy and metallurgical experimentation to establish so-called ore domains that are used to predict the performance of a plant and to design a process [8,9]. In the case of lithium ores, which contain a large amount of alumina, geometallurgical domaining is highly beneficial since the aggravated challenges of reactivity, fines behaviour, gel formation, impurity deportment, and residual stability are highly dependent on subtle mineralogical and textural distinctions. An example is that the lithium contained in readily exchangeable positions or loosely bound phases can be treated with less extreme leaching or selective recovery techniques, but the lithium contained in more permanent aluminosilicate structures may need to be activated by thermal or chemical treatments. Equally, the ratio of amorphous silica or reactive clay minerals may dictate the attainment of an acid leach, give a manageable slurry or result in a gel-like mass, which is virtually impossible to filter. Carbonates may neutralize the acid and increase the intake of the acid, and magnesium and calcium may produce scaling and complicate the purification of the product. These may be systematically variable in a deposit as a result of stratigraphy, alteration intensity, weathering profile, and sedimentary facies—precisely the sorts of patterns geometallurgical domaining is meant to record.

Nevertheless, geometallurgy is not enough unless it is supplemented by a decision strategy that directly balances recovery, product quality, cost, and environmental performance [10]. Practically, optimum processing paths of alumina-rich ores are very contextual. In certain systems, direct acid leaching (at atmospheric or high pressure) can provide simple kinetics and high extraction but requires extensive acid usage, high operability problems due to silica, and a heavy burden of neutralization/residue management. Activation methods such as roasting and then water leaching or other methods of thermal activation can be used to increase the availability of lithium and even alleviate undesirable gel behavior, but they come with energy requirements and air pollution that need to be minimized, hopefully by using low-carbon sources of heat and effective types of gas treatment. The alkaline or hybrid methods can be more effective in managing some impurities and silica behavior, and can produce a high-salinity circuit and residues with management issues of their own. New directions, such as selective sorbents, ion exchange, membrane separation, and electrochemical separation, are desirable in that they seek to select lithium and avoid dissolving aluminum and silica; however, they are challenged by the issues of selectivity in the presence of complex ore-derived leachate, regeneration chemistry, stability, and scalability [11]. The key to sustainable performance in all routes is the capacity to effect water loops, recycle reagents where feasible, reduce the amount of waste produced, and be physically stable and non-geochemically reactive during the closure timescales.

The environmental management factor is particularly crucial in the case of alumina-rich ores since the volume of residues may be high in comparison with the quantity of lithium generated, and the chemistry of the residues may be complicated [12,13]. Dissolving processes will always result in neutralization precipitates and salt-bearing streams, which create concerns about seepage, salinity, and long-term containment. Avoiding tailings rheology and filtration behavior may be challenging, especially when dealing with clay-

based feeds; this is because it becomes hard to implement low-risk storage methods like dry stacking without severe design. Such aspects as dusting, structural stability, and the presence of leachable constituents should be evaluated with the help of relevant characterization and risk-based models. Meanwhile, aluminosilicate-based residues can provide valorization opportunities, e.g., supplementary cementitious materials, geopolymers, zeolites, and adsorbents, in case variability, contaminants, and market constraints can be realistically considered [14]. Circularity. The idea of valorization is attractive, but it has to pass the same scrutiny as the basic lithium flowsheet, such as product specifications, environmental safety, and the risk of establishing secondary streams of waste. To frame the scope of sustainable lithium utilization from alumina-rich ores, **Figure 1** illustrates the full ore-to-product value chain and highlights the processing stages at which water, energy, reagent use, and residue management become critical decision points.

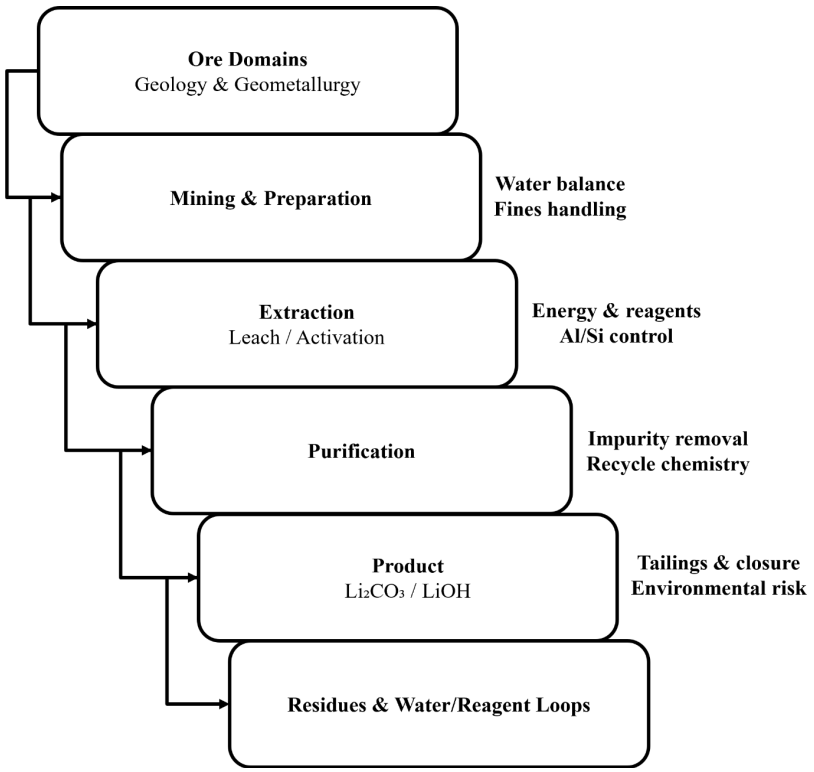

Figure 1. Conceptual ore-to-product value chain for alumina-rich lithium ores, illustrating major processing stages from ore domains to lithium products and identifying key sustainability checkpoints related to water balance, energy and reagent use, recycle chemistry, and residue management.

These are also technical and environmental complexities, which make it harder to compare project report performance and when researchers inter-compare the results among studies. Numerous published articles on the extraction percentage of lithium using a given set of leaching conditions do not offer a mineralogical context that could allow generalization of results. There are also other reports that include promising flowsheets without complete mass balances, impurity deportment, or residue characterization, thereby not being able to assess the true scalability and sustainability of a process. Missing solid-liquid ratio reporting, species stoichiometry versus acid-neutralizing capacity, particle size distributions, water chemistry, and purification downstream assumptions are additional aspects that contribute to increased inconsistency. Where gangue reactions may predominate the operation, as in the case of alumina-rich ores, such omissions may cause too much optimism. To overcome this, a literature review based on geometallurgy can be helpful, classifying literature by the properties of ores and domains, mapping domains to flowsheet families, and pointing to the minimum amount of data needed to determine the credibility of a technical and environmental performance assessment [15].

The review focuses mainly on clay-hosted, volcanic/

tuffaceous sedimentary, weathering-derived lateritic or bauxitic, and hydrothermally altered aluminosilicate lithium systems. Conventional brines and typical spodumene pegmatites are discussed primarily as reference systems, except where aluminosilicate gangue or lithium-bearing mica/clay phases impose processing constraints comparable to those of the alumina-rich systems defined above.

In line with this, this review allows synthesizing the existing information about sustainable exploitation of lithium in the alumina-enriched ores using a domain-aware method by relating geology and mineralogy to the choice of processing route and environmental conservation. Through the effects of deposit context and alteration/weathering paths on lithium deportment and gangue reactivity; how these two properties can be applied to the realms of practical geometallurgy and constrained by each; and how these operations delimit the viable options of extraction and purification methods. It is upon this basis that we consider the key flowsheet families—direct leaching, thermal activation, alkaline/hybrid routes, and new selective extraction methods—not only their lithium recovery but also impurity control, water and reagent recycling, residue, and operating at scale. Lastly, we combine sustainability factors using the prism of life-cycle and techno-economic drivers and pinpoint hotspots that tend to dominate the environmental footprint (e.g., thermal energy, reagent production, water management, residue storage) and define research priorities to reduce levels of dissolution of aluminum/silica, allow low-carbon processing, and enhance the results of residues.

The proposed domain-aware framework should be regarded as a conceptual synthesis and screening-level decision-support tool. It summarizes relationships reported across the literature but requires deposit-specific validation using quantitative mineralogy, standardized leach/reactivity tests, impurity deportment, water-recycle chemistry, residue characterization, and pilot-scale evidence before it can be applied predictively.

2. Ore Systems and Geometallurgical Domaining for Alumina-Rich Lithium Ores

Geometallurgical domaining offers a viable compromise between the geometallurgical behavior of alumina-enriched lithium ores in the industrial circuit and their formation in nature [16]. In these ores, the requirements of domaining are more urgent than in most traditional lithium feedstocks since in many such feedstocks lithium is generally distributed in fine-grained aluminosilicate matrices and usually the performance of processes only depends on bulk lithium grade but not the identity and reactivity of the host phases, the texture and particle size distribution, and the interactive behavior of aluminum, silica, and accessory impurities during the extraction and purification. Domaining thus emerges as an organizational paradigm used to explain variability in and between deposits, predict constraints to operability like rheology and filtration, and make decisions based on flowsheet families capable of attaining a robust recovery whilst managing reagent demand and residue risk.

2.1. Deposit Contexts and Formation Pathways Relevant to Alumina-Rich Lithium Ores

The lithium ores rich in alumina are formed due to various geological processes converging to a similar result, namely, the incorporation of lithium into aluminosilicate phases, which typically are abundant, fine-grained, and frequently react with acidic or alkaline environments [17]. Weathering is central in most environments, both in the disintegration of the primary silicates as well as the concentration of the relatively immobile elements and the redistribution of the alkalis. The retention of lithium by clay minerals formed in the weathering, exchange sites, or even incorporated into new aluminosilicate structures can vary with the fluid composition, pH, and accessibility of aluminum and silica. In areas where weathering profiles are extensive and lateritic processes are high, an assemblage of alumina-rich materials develops and may contain lithium as fine material, which is challenging to physically enrich.

Pathways related to sedimentary and basin settings are also prominent. The deposits of volcanic ash or tuffaceous material into basins may be subject to diagenesis, giving rise to clay minerals and mixed-layer phases which can acquire lithium, either as it was initially present in the source material, or as it was added by basinal fluids and redistributed through them [18]. The history of mineral systems in these kinds of systems, mineral system history

(depositional environment, early diagenesis, subsequent fluid flow, and temperature history), has a strong effect on the question of whether lithium is found in comparatively labile sites or is trapped in more ordered structures. Another route is hydrothermal modification, especially in areas that have volcanic or intrusive activity, which causes the circulation of fluid along aluminosilicate rocks. The hydrothermal fluids have the potential to transform the feldspars and micas into clays and other aluminosilicates, inject lithium, and produce mineralogical zoning, which is metallurgically significant. The implication that comes out as critical across these contexts is that the formation of a deposit leaves a fingerprint of the mineralogical makeup, which regulates the response to processes such that genetic knowledge is more than a mere academic context; it is a predictor of how a process is going to act, and a domain boundary of a domain.

Alumina-rich lithium deposits are formed by different geological routes, and each has specific mineralogical and metallurgical properties that have a direct impact on processing behavior and sustainability performance. The summary of these relationships is presented in **Table 1**, which connects the context of ore systems to hegemonic sensitivities and first-order processing implications [19].

Table 1. Alumina-rich lithium ore system contexts and expected processing implications.

Ore System Context	Typical Li-Host Setting (General)	Dominant Alumina/ Silica Matrix	Common Metallurgical Sensitivities	Likely "First-Look" Route Implications
Weathering-derived clay/lateritic profiles	Li distributed in fine aluminosilicates; enriched in fines	High clays; variable reactive silica	High fines, water demand, rheology risk; elevated reagent consumption if matrix dissolves	Favor selectivity-first strategies; avoid deep matrix dissolution when possible
Volcanic ash/tuffaceous sedimentary basins	Li associated with clay/ mixed-layer phases formed during diagenesis	Clays + amorphous/ poorly crystalline silica possible	Silica polymerization/gel risk; variable leach kinetics	Consider staged/hybrid or activation if gel-prone under acid
Hydrothermal alteration of aluminosilicates	Li introduced/redistributed with alteration; strong zoning possible	Altered feldspar/mica → clays; variable Fe/Ti	Strong domain variability; impurity release can spike in zones	Domain-based blending and route flexibility are important
Bauxitic/alumina-rich laterites with Li in fine fractions	Li may occur in fine aluminosilicate residues and coatings	High Al phases + clays; possible high Fe/Ti	High residue volumes; solids separation challenges; impurity management	Routes that minimize Al dissolution are preferred; residue planning becomes central

2.2. Lithium Deportment in Aluminosilicate Matrices and Its Processing Significance

In base-high-in-alumina ores, lithium is often not found as discrete lithium minerals, which can be liberated through a standard comminution and beneficiation procedure, but is present in clay minerals or in micas and mixed-layer aluminosilicates [20]. The term lithium deportment is applied here in order to highlight not only which minerals contain lithium but also the way lithium is attached to the minerals. Lithium can either fill interlayer exchange positions or be bound to surface adsorption on clays, replace octahedral or tetrahedral positions in the aluminosilicate lattice, or exist as small inclusions or amorphous phases. The extraction behaviors that are associated with these binding modes are very different. In stronger, weakly bound, or exchangeable positions, lithium can be available under moderately mild conditions, provided the conditions of the process environment are able to reach said positions without dissolving the entirety of the gangue matrix. In comparison, lithium substitution into resolute aluminosilicate structures will usually imply fiercer chemical aggression, heat motivations or extended reaction time, which may also hasten the disintegration of alumina and silica as well as aggravate downstream purification liabilities.

It is this association of lithium emission and gangue dissolution that represents the metallurgical problem of alumina-rich lithium ores [21]. During acidic circumstances, aluminosilicate dissolution can release lithium in addition to liberating silica-rich species and creating polymerized silica networks, which can be characterized as gelation and rheological catastrophes. The behavior of silica and alumina under alkaline conditions changes and poses various constraints, like requirements of desilication, precipitation, and salt build-up in recycle loops. Therefore, the geometallurgical approach considers lithium deportment as a main classifier of route choice, as it determines lithium selectivity to extraction, and the extent to which the tradeoff between lithium recovery and dissolution of gangue is likely to be severe [4].

2.3. Ore Attributes That Define Domains: Mineralogy, Texture, Reactivity, and Impurities

An operational domain model should be constructed on attributes that can be quantified with some sensible certainty and those that are associated with processing results. In the case of lithium ores that contain a high percentage of alumina, the mineralogy is considered the first-order control as it determines not only lithium bearing but also the dissolution/precipitation reactions that control agent consumption and operability. The relative abundance of clay minerals, micas, the remains of feldspar and amorphous silica and the presence of the aluminum bearing phase determine whether the leaching process is dominated by the fast reactions on the surface, or by the diffusion of the slurry through the changed layers, and whether the slurry will tend to develop settling behavior or gel-like states, which do not allow for filtration. Variability in acid-neutralizing capacity and the tendency to form secondary precipitation is also a consequence of mineralogical variability and is capable of re-encapsulating lithium or non-productively consuming reagents [22,23].

The texture and particle size distribution are also clearly domain-defining properties since the alumina-rich ores tend to produce extremely fine particles during mining and comminution, and the clays may exist as aggregates dispersible under shear or in the presence of a special water chemistry. Fine fractions have uneven lithium grades, but even assuming control of surface area, water demand, and lag behind rheology. This mineral assemblage can thus be very different in its behavior under different circumstances, such as the presence of lithium-bearing phases as discrete particles, as coatings, or as intimate intergrowths on sub-micron scales. These textural realities determine the existence of any pre-concentration possible, whether a lithium-based desliming is possible, and whether an agglomeration or a controlled conditioning is only required to sustain the pre-concentration performance of permeability and solid-liquid separation [24].

Reactivity indices will give a pragmatic means of reducing mineralogical and textural complexity into predictor forms. In lithium ores that contain alumina, reactivity is not a single parameter; acid consumption is dependent on carbonates and reactive aluminosilicates, silica gel propensity is dependent on both form and solubility of silica, the process conditions are conducive to polymerization, and aluminum dissolution is dependent on both mineral identity and kinetic accessibility. The domain definitions thus have the advantage of standard and similar proxies like consumption measures normalized to mass and to stoichiometric demand, temporal profiles of leachate compositions, and measures of slurry behavior indicators reflecting the onset of gelation or severe viscosity increase under typical conditions [25].

Impurity suites also complement the domain further since they affect extraction chemistry as well as the purification of products. Magnesium and calcium have the potential to propagate scaling and make the control of carbonate or hydroxide precipitation a difficult task [26]. Iron, titanium, and manganese can pose some filtration problems, absorb oxidants or reductants, and pose a risk of contamination of a product if not eliminated efficiently. Halides and sulfates may serve in recycle cycles and affect corrosion and crystallization, as well as discharge limitations. At meaningful concentrations, trace elements can determine the risk of permitting and residue classification in the absence of domineering chemistry. Since these impurities are frequently related to certain stratigraphic or alteration areas, incorporation into domaining assists in optimizing processing, but also in mine planning and selective blending plans to stabilize plant feed.

2.4. Constructing Practical Geometallurgical Domains for Route Selection

Domaining in this review is not aimed at establishing some general taxonomies but at helping to translate the attributes of ore into flowsheet options and the sustainability consequences of the latter. New domains tend to be more effectively defined as combined descriptors encompassing lithium deportment, gangue reactivity, and operability constraints as a combination. The alumina-rich lithium ores usually have a domain model that distinguishes between those materials where lithium is fairly available with only a limited need to dissolve aluminosilicate instability and those materials where the release of lithium cannot occur without vigorous assault against the alumina-silica framework [17,27]. The further domain limits within each broad category are given in terms of the predominant process risk, e.g., strong gelation tendency in acidic conditions, high buffering capacity provided by carbonates, which causes a rise in acid consumption, high magnesium and

calcium, which increases scaling and complexity of purification and high salt content, which limits water recycling and changes the chemistry of the residue.

One of the main aspects of practical domaining is the understanding that boundaries are supposed to indicate step changes in the process response and not gradual changes in the individual assay value. As an example, even a minor increase in reactive silica or in the proportion of amorphous phases can cause an out-of-proportionate increase in the gelation propensity and filtration failure under otherwise similar leach conditions. Equally, changes in the type of clay and mixed-layer sequence may modify the efficiency of thermal activation or modify the selectivity of leaching. Validation of domains thus needs to be correlated with metrics at scale that have teamwork of metallurgical tests, such as lithium extraction in real-world conditions, index of hardware, solid-liquid separation properties, how impurities deport to solution and solid, and stability of recycled water chemistry [28,29].

When domains are validated, they present decision logic that is explicit in route selection. The materials that exhibit more labile lithium binding and reduced gangue dissolution demands are the most promising candidates for the selective extraction concepts that will reduce the levels of aluminum and silica dissolution. Structurally bonded lithium materials with a highly reactive matrix can be a suitable material to use with the activation processes aiming at modifying mineral structure before leaching and potentially enhancing kinetics and other problematic silica behavior, though at an energy sacrifice to be controlled. Buffering mineral-dominated materials can either be preconditioned or use other reagent strategies to prevent unnecessary use. The impurity profile of a material that highly punishes purities may impose control requirements on impurities at the front of the purity process, or a route may involve a strategy of not introducing purifying impurities into solution [30]. Through this, domaining becomes a flowsheet avoidance mechanism, and projects are designed based on the most limiting ore behaviors and not average grade.

2.5. Characterization Workflows and Minimum Reporting Requirements for Domain Assignment

Solid domaining requires characterization workflows that are not only technically defensible but also usable in practice. In the case of lithium ores rich in alumina, quantitative mineralogical analysis forms a basis, as lithium deportment cannot be determined using bulk analysis. Identification of phases and semi-quantitative estimation of abundance of important clays and aluminosilicates are offered when using X-ray diffraction, whereas textures, associations, and fine-scale occurrences that affect liberation and accessibility to reactions are resolved by electron microscopy and microanalysis. Statistically confident automated mineralogy may be needed where grain size and complexity allow meaningful segmentation, but exceptionally fine clays may need supplementary methods, e.g., spectroscopic methods or indirect proxies associated with reactivity [31].

Since the response of processes in these ores is frequently a coupled reaction, and not a single dissolution step, characterization can no longer be carried out by identification of a mineral, as it is now necessary to test the reactivity of the reactants in controlled reactivity experiments [32]. Leach tests, standardized tests, and supervised tests under controlled conditions may give comparative indices of lithium release, aluminum dissolution, and silica behavior, and time-dependent solution chemistry to determine whether the reaction is heading toward gelation or secondary precipitation. Rheological measurements, settling tests, and filtration trials at representative pulp densities provide early warnings of risks in scale up that otherwise would not be detected in small, dilute laboratory tests. The characterization of water chemistry is also important since clays are ionic strength- and ion-specific sensitive, and recycled water composition can change radically with accumulating salts, changing dispersion, flocculation, scaling, and precipitation equilibria.

Domain-based claims must have a minimum set, along with claims in the SCI-standard format, to be able to compare them and manage the comparability between studies. Studies must at least provide their mineralogical context of lithium hosting and that of reactive gangue, the particle size distribution with fines fraction in a manner that allows comparison, the complete solution chemistry of major elements that dominate reagent demand and downstream purification, and a characterization of their residue that addresses both mass balance closure and environmental stability issues [33]. In the absence of these elements, there is little consisten-

cy between truly selective lithium extraction and seemingly selective extraction due to the wide-scale dissolution of the matrix, and there is little indication of whether a flowsheet can be scaled or was just a lab result.

The systematic characterization of geological variability into implementable processing choices necessitates a reliable and clear-cut framework of characterization. **Table 2** is a summary of core domaining descriptors and minimum data required to be reliable predictors of processing response, operability risks, and sustainability performance of alumina-rich lithium ores [34].

The translation of geological variability into processing and sustainability decisions follows a structured workflow, summarized schematically in **Figure 2**.

Table 2. Geometallurgical domaining descriptors and minimum characterization dataset.

Domain Descriptor Class	What Should Be Measured/Reported	Why It Matters for Processing	What It Predicts (Typical Outcomes)
Lithium deportment	Li-host phases and binding mode (exchangeable vs. structural); micro-textures	Determines whether selective extraction is feasible	Route family viability; expected selectivity vs. matrix dissolution
Mineralogy of Al/Si matrix	Quantitative phase assemblage; reactive vs. crystalline silica indicators	Controls Al dissolution and silica polymerization	Acid/alkali demand; gel propensity; neutralization solids volume
Particle size & fines behavior	Particle Size Distribution (PSD) including <10–20 µm fraction; dispersion tendency; settling/filtration response	Governs rheology, thickening, filtration, washing losses	Throughput limits; water demand; feasibility of dry stacking/paste
Reactivity indices	Standardized leach tests under defined Solid-to-Liquid Ratio (S/L); time-dependent Al/Si/Li release	Captures coupled reactions better than grade alone	Consumption curves; onset of gelation; kinetic windows for staging
Impurity suite	Major cations/anions and key traces; carbonate buffering; Mg/Ca/halides/sulfate	Drives purification complexity and recycle chemistry drift	Scaling risk; corrosion risk; purge requirement; product-spec constraints
Residue/tailings properties	Residue mineralogy, salinity, leachability indicators, permeability/strength proxies	Determines storage design and closure risk	Lining/collection needs; dewatering strategy; closure feasibility

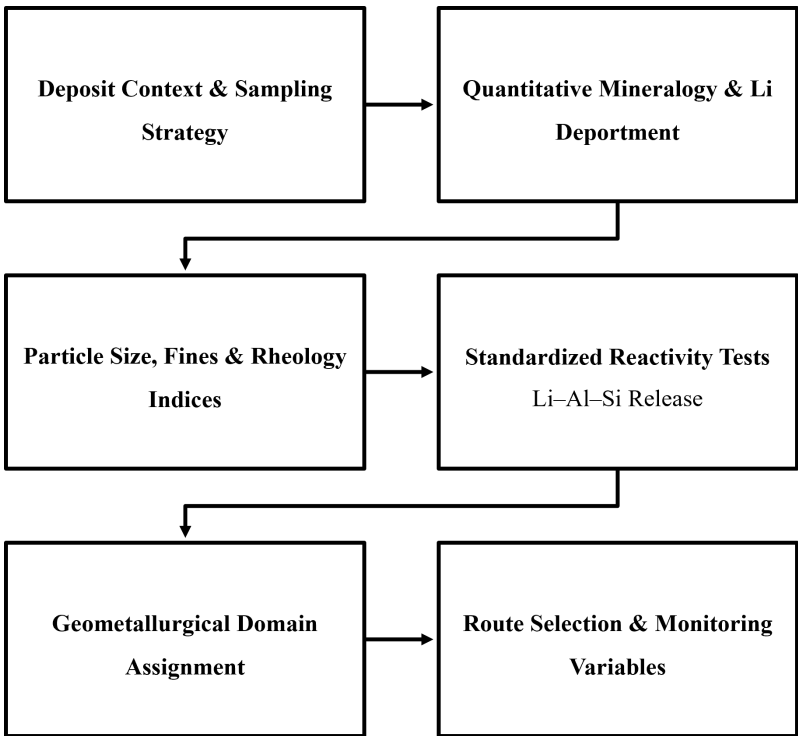

Figure 2. Geometallurgical domaining workflow for alumina-rich lithium ores, linking deposit context, mineralogy and lithium deportment, fines and rheology behavior, standardized reactivity testing, domain assignment, and processing route selection.

A complex of mineral deposition conditions, lithium deportment, interactive behavior of a gang, texture-modulated operability limitations, and impurity suites together offer the support of a domain frame that is directly exe-

cutable [35]. The following section expands on this basis by projecting domains to processing route families and the development of a decision logic that provides an explicit consideration of recovery, operability, impurity control, and sustainability performance.

3. Processing Route Selection by Domain: Flowsheet Families and Decision Logic

Section 2 confirmed that the lithium ores with alumina content are not separably put into a single processing class since lithium deportment, aluminosilicate reactivity, fines behavior, and impurity suites fluctuate systematically between deposits as well as between orebodies themselves, in most cases. Instead of ranking routes individually, their interactions to face the joint challenges that characterize alumina-rich systems are considered, i.e., simultaneous dissolution of aluminum and silica, gel formation and rheology changes, impurity retention in recycle loops, and volumes of residue that can dictate environmental hazard and operating cost.

3.1. Flowsheet Families for Alumina-Rich Lithium Ores and Their Defining Mechanisms

There are many flowsheet families of processing options for alumina-rich lithium ores that differ in the method of lithium liberation from aluminosilicate hosts, as well as in the treatment of gangue reactions [17,33]. Direct leaching pathways seek to isolate the lithium-bearing phase in a solitary chemical reaction, usually through the application of an acidic medium and occasionally through the application of higher temperature or pressure in order to speed up the reaction. These pathways are critically straightforward and can provide high lithium recovery in the laboratory, though the major query concerning alumina-bred ores is whether lithium dissolution is possible without producing in-depth disintegration of the alumina silica framework and the general formation of slurries, which are hard to manage and filter. The economic usefulness of direct leaching is not hence as dependent on the natural grade of lithium as upon the selectivity of dissolution and the convenience of the leachate and residue thus obtained.

In thermal activation routes, a pre-treatment stage is added aimed at converting lithium-bearing aluminosilicates into a form where lithium can be leached more easily, such as by converting lithium into water-soluble or weakly bound salts or by breaking up mineral structure to open it up [36]. These paths can involve roasting and various additives or reagents, and then the addition of water to recover the lithium as a solution, and then purification and solvent recovery may be performed. Their unique benefit lies in the fact that they occasionally decouple the process of lithium recovery and massive gangue dissolution, thus boosting the degree of slurry behavior and decreasing the load of downstream neutralization. Their characteristic penalty is the demand for energy and the related emissions that should be compared to the chemical intensity that would be avoided in direct leaching.

Alkaline and hybrid paths aim at capitalizing on the solubility and precipitation contrast between conditions with caustic and carbonate [37]. Alkaline conditions in certain systems can decrease the tendency of silica gel formation in comparison to acidic leaching, but alkaline conditions themselves cause control problems such as desilication requirements, high ionic strength recycle circuits, and the formation of residues with chemistry and permeability that are difficult to handle. Hybrid methods can take advantage of staged pH control or sequential leaching conditions in order to reduce the period that a slurry is in a regime where gelation or uncontrolled precipitation is likely to occur.

The last family is selective extraction and separation concepts that are specifically created to reduce dissolution of aluminum and silica, e.g., ion exchange, sorbents, membrane-assisted separations, or electrochemical [38]. Ideally, these methods are very much compatible with sustainability goals since they seek to extract lithium from solutions or even slurries without employing a lot of reagents and also producing little residue. Their practice has relied on their selectivity in complex matrices, foulant strength, competing ion strength, regenerant chemistry and scaffold ability. They are most believable in alumina-rich ores, when combined in a domain-dependent flowsheet to allow the formation of a solution composition that gives them selective capture, yet has no impact on overall recovery.

3.2. Translating Domains into Route Priorities: The Logic of Selectivity, Operability, and Closure

The process of choosing the routes to be used in the extraction of alumina-rich lithium ores can be best described as a constrained optimization problem [39]. The basic requirements are lithium recovery and purity of the products, but the operability requirements and the environmental closure requirements often dictate the route that can be taken. Dominating offers the constraint set by stating that lithium is likely to be accessible when the conditions are mild, that the slurry is likely to transform into gel-like when the conditions are acidic, that buffering minerals are likely to inflate acid usage, and that impurity suites are likely to cause significant downstream loads. The decision logic starts with the lithium deportment and continues through a series of constraints: the possible lithium-to-water with gangue reactivity and gel propensity limits the possible feasible leaching environment and residence time; solid liquid separation strategies are limited by impurities behavior, impurities suites limit purification choices, and water-recycle limits.

Where domaining shows that lithium is fairly labile and the dissolution of aluminosilicate does not require the attainment of significant lithium release, then the concepts of selective extraction and gentler leaching are of higher priority. The overall philosophy is to minimally place aluminum and silica into solution, thus minimizing the use of reagents and therefore easing the purification. However, in cases where the lithium is structurally fixed in stable aluminosilicates, and release necessitates significant matrix disruption, thermal activation, or staged hybrid systems are more competitive, as they can enhance the lithium release in addition to controlling the amount of uncontrolled dissolution in the later stages of leaching [40]. In high gel propensity domains with acidic regimes, route choices have to be negative to silica polymerization conditions, whether by switching to activation and leaching water, or by maintaining acidity and temperature during operations in staged operations, or by operating in alkaline/hybrid regimes where gelation is not favored, with other constraints kept within manageable limits. In areas where neutralization is predominant, not only chemical cost, but also the load of salt and residue due to neutralization and recycled reagent; paths which decrease the stoichiometric cost of neutralization, or allow internal recovery of reagents, are at a relative advantage.

Notably, the route selection should not be an afterthought, but it should take into account the behavior of closure and residue. The cost-effective and socially acceptable way of extracting a mineral may be a route that results in high yields but leaves residues with high salinity, poor geotechnical characteristics, or that are intractable. These threats can be preempted by residue chemistry by domaining due to the fact that residue chemistry is mostly related to the ore mineralogy and the route chemistry of choice [41]. A decision framework that instantiates residue and water-loop restrictions and metallurgical measures is thus vital towards sustainable utilization as opposed to short-term recovery maximization.

3.3. Direct Leaching Routes under Domain Constraints: When Simplicity Becomes Complexity

It seems that direct leaching, most frequently in acidic media, is appealing due to the possibility of making it a relatively compact flowsheet preparation, leach, solid-liquid separation, purification, and product precipitation [42]. However, in ores containing large concentrations of alumina, direct leaching would become tricky as the leach step solubilizes massive quantities of both aluminum and silica as well as lithium. The leachate that is obtained is usually subject to lengthy neutralization and precipitation processes to eliminate aluminum, iron, and other compounds, which consume more reagents and form large volumes of precipitates. At the same time, there is a risk that the silica behavior switches to networked polymers, resulting in filtration viscosity build-up, gelation, and ineffective filtration. These problems are compounded by the high surface area of fine clays, which has a quickening effect on the dissolving gangue and increases the amount of water needed.

Areas where reactive clays and amorphous silica are prevalent are thus the most troublesome to reactive direct acid leaching [43]. In this area, the higher lithium recovery through augmentation of temperature or acidity may be countered by swifter heightening of operational fines, such as the blinding of filters and the occurrence of an unstable precipitation pathway downstream. Even at lab-

oratory-scale high extraction of low solid fractions, scale-up can fail due to changes in industrially important slurry densities and recycle water composition, which change slurry behavior to regimes dominated by gelation and bad settling behavior. Consequently, direct leaching is most justifiable in the areas where lithium leaching is possible in the absence of extreme dissolution in the matrix, when silica exists in less active forms, and when the impurities may be eliminated without excess neutralization. The lack of these conditions can conceal the transfer of complexity to water management and residue management, impairing the sustainability objectives.

3.4. Thermal Activation and Roast–Leach Routes: Decoupling Lithium Recovery from Gangue Dissolution

Thermal activation paths overcome the fundamental limitation of direct leaching, where the mineral structure is changed before aqueous extraction [44,45]. Activation can be used in ores with high alumina content, in which lithium is held in a crystalline, structure-bound form, to raise the proportion of lithium to be water-leachable or can be obtained under milder chemical conditions. The change can minimize the dissolution of aluminum in the leach phase and eliminate the formation of silica gel by limiting the duration during which the slurry remains in a high-acidity regime. Roast-leach processes are also more likely to result in lower concentrations of dissolved aluminum and silica in the resulting leach solution, leading to easier downstream purification and potentially smaller precipitates of the neutralization.

The main tradeoff is the energy and emissions cost relating to heating, as well as, in certain instances, the gaseous by-products [46]. The domain viewpoint suggests that thermal activation is enhanced when the ore is pushed towards more ordered or stable hosts that are aluminosilicate, and that the gel propensity is elevated when subjected to acid leach conditions. It is also desirable that the fineness of the ore would otherwise cause serious thickening and filtration issues when leaching the ore directly, since a water leach after activation may be more rheology-tolerant. Thermal routes, however, have to be analyzed in the bigger picture, such as the potential of heat integration, the carbon intensity of the energy source, and the chemistry of the activated solids and residues. In other fields, activation can cause secondary phases, which are difficult to manage, or cause soluble salts that build up in recycled water. Activation is thus not considered by the decision framework as a universal solution but a domain-based lever to enhance selectivity and operability where chemical-only pathways are no longer sustainable.

3.5. Alkaline and Hybrid Approaches: Controlling Silica while Managing Salts and Recycle Chemistry

Another reaction to silica-related limitations is alkaline routes and hybrid pH routes. The dominant goal in most systems that contain alumina is silica polymerization control and enhanced solid-liquid separation, and switching the chemistry to less acidic conditions can be helpful. Basic impurity control strategies may also be supported under alkaline conditions and are likely to coincide with some precipitation mechanisms of aluminum and iron. However, the alkaline processing of alumina-rich ores comes with its own set of limitations, which are usually related to recycle chemistry and salt treatment. Dispersion and flocculation of clay. The high ionic strength solutions may alter the dispersion and flocculation behavior of clay, affect scaling, and make crystallization and finishing of products difficult. The desilication process may be needed to avoid silica carryover, and this process can also produce other residues that are also stable and have to be leached in the same manner as silica [47,48].

The objectives of hybrid regimes are to take advantage of the advantages of acidic and alkaline regimes through staging reactions and controlling the location and timing of dissolution or precipitation of specific species [3]. Indicatively, a flowsheet can employ a mild leach to mobilize lithium and restrict the dissolution of aluminum, after which specific impurities can be removed, and the pH can be controlled. The viability of these schemes is highly domain-dependent since staging is only useful in cases where the mineralogy of the ore provides a window of selectivity. In the case of lithium trapped in stable structures, there may still be a requirement to activate or slow down the reaction, which reduces their benefit. In areas containing impurities and liable to recycling build-up, hybrid programs will have to be constructed with clarified strategies of purge and make-up, averting long-term drifting of water

chemistry, which damages operability and environmental conformity.

3.6. Integrating Downstream Purification and Product Selection into Route Choice

Downstream purification is not a generic addition to alumina-rich lithium ores; in many instances, it is the economic and operational focus of the plant since it defines whether lithium can be produced to specifications without being prohibitively expensive in terms of reagents and excessive amounts of waste. The choice of route should thus not only be determined by the manner in which lithium goes into solution, but also by the contents of the solution and the amount of precipitates formed in the extraction of impurities. Aluminum and silica are high in solution, which may cause a lot of neutralization and may entrap lithium in precipitates unless pH control and precipitation kinetics are closely controlled. Magnesium and calcium may cause co-precipitation losses, scaling, and product contamination, whereas iron and manganese may introduce extra oxidation or precipitation processes [49].

Decisions on flowsheets are also fed by product choice. The conversion between lithium carbonate and lithium hydroxide may alter the impurity tolerance, crystallization behavior, and reagent demands [50]. Some routes tend to give solutions that are preferable to one of the product pathways over the other, especially in the presence of high levels of sulfate, chloride, or carbonate. A domain-aware framework thus considers product selection a co-selection, not a downstream consideration, since the most sustainable path is one where solution chemistry, purification strategy, and product finishing are in concert with each other to minimize losses, over-addition of chemicals, and reduction in volume of residues.

3.7. A Domain-Aware Route-Selection Matrix as a Review Synthesis

An application of alumina-rich lithium ores is a useful synthesis on a qualitative route-selection matrix in which domains are defined by the constraining constraint and routes are contemplated by their ability to deal with the constraining constraint throughout the system. The labile lithium and low gangue dissolution domains in such a matrix require selective extraction and mild leaching since these two techniques maintain selectivity and reduce the amount of residue produced [51]. Areas that are controlled by de-gelatinized silica and active clays discourage vigorous direct acid leaching and augment the relative appeal of activation and water-leach designs, assuming that energy and emissions are handled responsibly. Areas that have a high buffering capacity are punitive of high-acid pathways because of consumption and neutralization loads and prefer measures that may decrease stoichiometric neutralization or allow reagent recovery. High magnesium and calcium domains punish paths that move these ions into solution unless strong scaling and impurity control have been designed into it, and determine whether closed-circuit water operation is possible and how residues should be classified and stored.

Referring to the domaining framework, **Figure 3** shows a simplified decision tree, which displays the limits of feasible processing paths of alumina-rich ores set by lithium accessibility, gel propensity, and activation response [34]. The effects of ore domaining on flowsheet selection can be generalized into a qualitative selection model. **Table 3** plots the typical domain behaviors onto the relative aptitude and limitations of the significant processing route families of alumina-containing lithium ores.

What is important about this matrix is not a prescription of the Single Best Route but a set of tradeoffs identified and clear to quantifiable ore qualities. It is also useful in setting research priorities: effective application (with penalties) wherever a field has emic flowsheets should result in innovations (enhancement) of the possible processing window, through enhancing selectivity, performance of silica, applied thermal intensity, or closed-loop reagent and water management [40]. This domain-to-route reasoning establishes the technical deep dive of Section 4 upon which the principal operability and impurity control issues are considered throughout the value chain, with a focus on the control points that establish whether the success of laboratory work can be applied to create sustainable industrial practice.

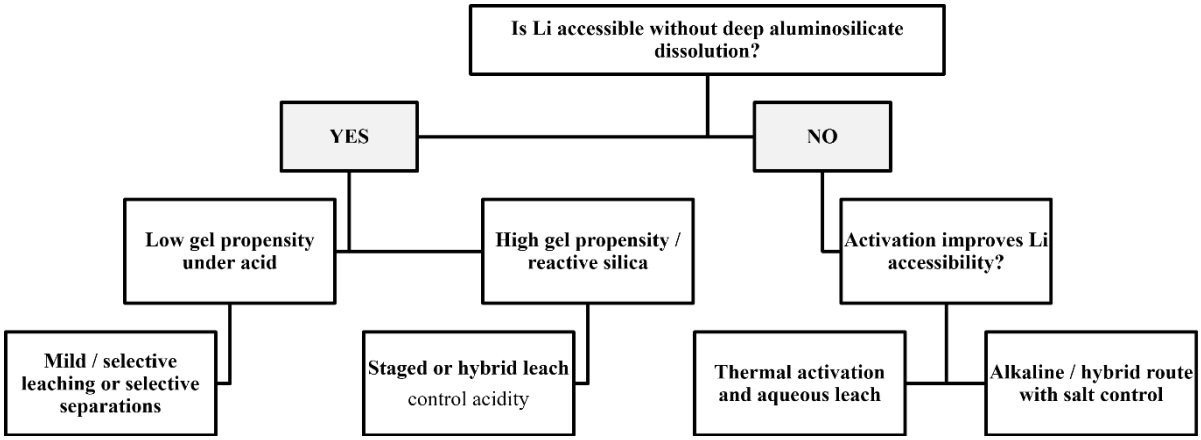

Figure 3. Conceptual domain-to-route decision tree for alumina-rich lithium ores, illustrating how lithium accessibility, silica gel propensity, and response to activation guide selection among leaching, activation-based, alkaline/hybrid, and selective extraction routes.

Table 3. Domain-to-route selection matrix (qualitative) for alumina-rich lithium ores.

Representative Domain Behavior	Direct Leaching (Acid)	Thermal Activation + Aqueous Leach	Alkaline/Hybrid Routes	Selective Separations (Ion Exchange (IX)/Sorbents/Membranes/Electrochemical)
Li relatively accessible; low matrix dissolution needed	Often feasible if Al/Si dissolution is limited	Feasible but may be unnecessary	Feasible if salts are manageable	Strong candidate if upstream conditioning keeps Al/Si low
Strong acid gel propensity/ reactive silica	High operability risk unless carefully staged	Often favored for operability	Sometimes feasible; watch salt/recycle drift	Feasible if solution is conditioned and colloids controlled
High buffering capacity (carbonates)	High acid consumption; large neutralization solids	Can reduce chemical burden if activation is effective	Potentially advantageous; manage carbonate/alkali balances	Possible if mild mobilization step works without high reagent use
High Mg/Ca (scaling/co-precipitation risk)	Purification burden increases	Often improves liquor quality; still must control Mg/Ca	May shift scaling location; manage ionic strength	Selectivity must withstand competing ions; fouling/scaling controls needed
High halides/sulfate (recycle salt accumulation)	Corrosion + crystallization constraints	May introduce soluble salts; purge design critical	Recycle control critical; purge/treatment often required	Media durability/selectivity under high ionic strength is limiting

4. Critical Technical Challenges and Control Strategies across the Value Chain

The domain-to-route reasoning in Section 3 points out a key fact about alumina-containing lithium ores: the performance is not people-to-lithium dissolution. Rather, the restricting factors are usually coupled phenomena which manifest themselves immediately when the ore is reduced to a slurry and is subjected to the reactive process environments. These processes are aluminum and silica mobilization, gelation and rheology changes, solid-liquid separation breakdown, deportment of impurities into solution and product, and resultant generation of large quantities of chemically complex by-products, and are highly interdependent [52]. A control measure that enhances lithium recovery may also degrade filtration, increase neutralization pressure, or cause water recycle chemistry instability. Section 4 thus examines the most significant technical issues that can be seen throughout the flowsheets of alumina-rich ores and explains the process control sources that decide whether a concept can be made to work at scale. Emphasis is made on mechanisms and control points over one particular and best flowsheet, as the set of solutions will be different depending on the ore domain.

4.1. The Aluminum Challenge: Dissolution, Neutralization Demand, and Downstream Burden

The most common cation that is mobilized during aggressive treatment of alumina-rich lithium ores is often aluminum, and its behavior is often a determining factor in operating cost as well as flowsheet complexity. When in an acid system, the rate of dissolution of aluminum is greatly influenced by the temperature, acidity, and surface area,

creating pregnant liquors that need a lot of neutralization or even hydrolysis to eliminate aluminum before lithium recovery. These steps of removal are not merely reagent-intensive, but may also result in excessive loss of lithium by co-precipitation, adsorption, or entrainment, particularly when the precipitation takes place in the presence of gelatinous silica or fine suspended solids. Secondly, the volume of precipitates that form in aluminum-bearing refiners can make up high-volume products that represent a critical element of tailings care and closure responsibilities [53].

Good management of aluminum commences at the stage at which the flowsheet is selected. Dissolution of the alumina-silica structure in general will invariably cause an alumina burden downstream; hence, selectivity upstream is the strongest control lever. Direct leaching systems utilize control of aluminum by moderating the degree of leaching, and using kinetic or thermodynamic windows within which the release of lithium but not of aluminum is significant. It is also domain-dependent, as certain ores will release lithium early in the reaction, and some will need a deep attack on the lattice. In thermal activation, an aluminum control is shifted further upstream by allowing the leaching of lithium to be done in milder aqueous conditions, which minimizes the extent of solubilization of aluminum and reduces extensive neutralization [54].

Where aluminum is introduced to the solution, downstream control is reliant on the control of precipitation pathways and the control of uncontrolled secondary reactions. One can also develop precipitation in such a way that the lithium is not co-precipitated, but pH progression, temperature, residence time, and mixing must be carefully considered since rapid pH variations or local over-neutralization may result in fine precipitates that incorporate the lithium and foul the separation equipment. The operational implication is that the extraction of alumina in alumina-rich systems is not a straightforward step of adding base to a target pH but a controlled reaction system, which must be incorporated with solids extraction and water recycling measures to prevent the runaway consumption of reagents and the unstable sludge behavior [55].

4.2. Silica and Gel Formation: Mechanisms, Indicators, and Avoidance Windows

The most critical operability limitation in the processing of alumina-rich lithium is often silica behavior, especially in clay-rich domains and ores that contain reactive or amorphous silica [40,56]. When silicic species are released under acidic conditions, as a result of dissolution of aluminosilicates, they can polymerize and form colloidal silica or a three-dimensional gel network. Gelation raises the viscosity of slurries, hinders active mixing, suppresses settling, obscures filters, and may fix dissolved species in a semi-solid structure. The empirical implication is that a seemingly successful procedure in a low-solids lab leach experiment may not be functional at that-which-is-industrial pulp concentration, where silica concentration and collision rates are higher, and recycle water chemistry can allow polymerization and flocculation routes to happen that were not observed in fresh-water experiments.

The best silica control measure is not to use regimes that promote polymerization at the time when slurry has high levels of reactive silica and dissolved aluminum. This may be by route choice, which may involve moving to an activation and then water leaching, or staged reaction design where lithium is obtained at an early stage under conditions that do not encourage silica release and the slurry is not allowed to remain long in the strongly acidic, high-temperature conditions. In those systems in which direct leaching is sought, silica control is often based on the time-temperature-acidity path as opposed to an individual set point. The potential to reduce the probability of the development of gel can be achieved by limiting the peak silica concentration in solution, reducing the residence time of solution at high propensity of polymerization, and controlling the sequence and location in which neutralization agents are added [47].

Silica control is also operationally needed with early indicators and test methods indicating the actual conditions of the plant. Outright percentages of extraction are not used to indicate that a slurry is approaching a gelation point. The scale-up decision is more informed by indicators of viscosity change, flux decay of filtration and development of stable colloids. Since the gelation behavior is responsive to ionic strength and individual ions, particularly in the recycle-heavy circuit, testing protocols should account for the water chemistry drift [57]. With this, however, a flowsheet can be optimized in conditions that are not reflective of steady-state operation, and then give unexpected gelation when salts are built up in recycle loops.

4.3. Solids Handling, Rheology, and Solid–Liquid Separation as Scale-Up Limiters

Lithium ores that contain alumina are often characterized by high particle sizes and clay minerals which have high water binding properties, dispersion sensitivity and shear-dependent behavior [17]. These properties have been found to influence almost every unit process, but can be limited to thickening, filtration, and tailings dewatering, where low permeability and poor settling will cause a flowsheet to become impractical despite high lithium recovery. Rheology is not a secondary factor; it is a primary factor of throughput, equipment size, energy consumption and water re-use.

The initial checkpoint is management of the particle size and the fines. Certain flowsheets try to deslime, but this is to enhance downstream separation; in most deposits, the fine fraction may contain a significant amount of the lithium, thereby making aggressive desliming a direct penalty on recovery. On the other hand, storing all the fines may cause unstable performance of the thickener and reduce the possible pulp densities, heighten the size of leach tanks, water consumption, and volume of tailings. The proper methodology is dependent on the manner in which lithium is divided among size fractions, which is likewise an area property associated with lithium host textures. The most common practical solutions are conditioning measures that suppress dispersion and flocculation behavior, and physical measures, either attritioning or controlled agglomeration, which aim at permeability without necessarily grinding finer [33,58].

The second control point is the combination of chemical reactions and separation stages. Thickening and filtration can also be accompanied by the precipitation of aluminum-, iron-, or silica-related phases in alumina-rich systems and modulate the particle size distribution and surface properties, both of which are counterproductive to performance. The neutralization and hydrolysis steps that are used in processes require the process to be constructed in such a way that separable solids can be produced with a uniform floc structure and low gelatinous nature. This need drives the flowsheets towards removal in stages with specific clarification stages and towards running envelopes that do not produce ultra-fine, compressible sludges. Suspended solids carryover becomes of particular concern in recycle-dominated water circuits, where small changes in the amount of colloids may build up and slowly compromise the performance of the thickener, or cause a slow-moving operability failure that is not immediately apparent in short tests [59].

4.4. Impurity Deportment and Product-Specification Risk across Routes

The presence of impurities in lithium ores rich in alumina can be even more consequential than in traditional lithium feedstocks due to the release of impurities being based on the same aluminosilicate structure as lithium and because of the entrainment and adsorption losses caused by fine particles [60]. The most important impurities are aluminum and silica because of the impact on the volume and process effects, magnesium and calcium because of the scaling and co-precipitation, iron and manganese because of the risk of color and contamination, and anions such as chloride and sulfate because of the corrosion, crystallization limitations, and discharge. Even in cases where relatively small amounts of some of these species might be found in the ore, they will accumulate in recycle loops or in concentrated liquids near crystallization.

The salient issue is that the purification process may result in the formation of lithium losses, which cannot be accurately measured unless a stringent mass balance is kept. The lithium may be lost by co-precipitation with the new silica or iron particles, adsorption onto the new particles, or entrainment in the poorly settled sludges. These processes become more intense when it pours, solids are gelatinous, or when the flocculated structures entrap liquor. Hence, the issue of impurity removal should turn out to be a coupled recovery problem, and not a purification problem. The control strategies include not only the selection of suitable separation technologies, but also the design of the chemistry and kinetics of precipitation in such a way that the impurity solids are in separable and low-entrainment morphologies [61].

Flowcharts are also limited by product specifications. The purity of lithium carbonate and lithium hydroxide is highly sensitive to a variety of cations and anions, and various pathways may be able to withstand various impurity profiles. To illustrate, chloride and sulfate may have an effect on crystallization behavior and product washing needs, and magnesium and calcium may co-pre-

cipitate or cause scaling in evaporative concentration steps. In systems containing a lot of alumina, where compositions of leachate may change with ore domain, the design of product selection and purification should be flexible so that swings in composition do not result in huge losses or frequent circuit disruption [62,63]. This usually gives preference to purification methods that are adjustable to feed variability, and with strong balances in water and reagent recycling.

4.5. Separation and Purification Toolboxes: Matching Unit Operations to Complex Liquors

The difficulty of purification in processing lithium rich in alumina is frequently a series of separations and not necessarily a decisive step [64,65]. Early clarification and solid removal are usually necessary to both safeguard downstream equipment and to avoid fouling of the separation media. The impurity removal process more often involves precipitation, which is recommended for the removal of aluminum, iron, and other metals, though with strict staging to prevent the formation of sludges that are hard to dewater, and also to ensure lithium losses are not generated. In the case of predominant precipitation, the design question is how to eliminate impurities with minimal reagent consumption, as well as with the generation of high-volume residues.

Solvent extraction and ion exchange may be able to provide more selectivity for individual impurities, and may minimize the quantity of neutralization solids, but their operation is affected by liquor composition, competing ions, and the presence of colloids and organics, which may cause fouling or phase disengagement [66]. Selectivity can be lowered, and the reagent used more intensively to regenerate the reagent in high ionic strength and complex speciation in alumina-rich ore liquors. Membrane-based methods are capable of performing the targeted separations or water recovery but are susceptible to scaling and fouling in silica- and aluminum-rich systems. Consequently, these technologies are in general not single-purpose tools; they perform optimally when used in combination with upstream controls that restrict the entry of the species that lead to instability, and in this regard, colloidal silica and fine suspended solids.

Through a set of toolboxes, there exists a recurring theme that the purity operation is determined as much by the upstream production of liquor and solids as by the downstream unit operations. A domain-sensitive flowsheet will, thus, not only focus on upstream selectivity and stable slurry behavior to enhance the efficiency of leaching but also render advanced separation options possible. In situations where the targeted upstream controls are not sufficient to avert elevated levels of aluminum and silica in the solution, bulk precipitation and neutralization prevail as the dominant means of purification, resulting in bulk precipitation and large levels of residue and increased sustainability issues [67]. In this regard, the purification toolbox enhances the domain-to-route logic of Section 3: the more an ore domain dictates extensive matrix dissolution, the more the downstream plant is a chemical management system, not a selective lithium recovery system.

4.6. Materials of Construction, Corrosion, Scaling, and Operational Reliability

In addition to chemical and separation constraints, the lithium processing of alumina-rich lithium can tend to be extremely demanding on the equipment and materials for building [68]. The release of acids during high temperatures can encourage corrosion, and, therefore, the choice of alloys, linings, and maintenance plans must be selected with great care. Circuits containing chlorides increase the risk of corrosion to an even greater extent, especially in high-temperature and acidic environments. Scaling is a parallel reliability risk, which is often associated with calcium and magnesium salts, silica deposition, and pH and temperature changes during neutralization and concentration. If such technologies are implemented, scaling may decrease the heat-transfer efficiency, plug lines, and deteriorate the performance of the membrane or ion-exchange.

The reliability in the operation of these systems depends on controlling the entire circuit chemistry, such as the composition of recycle water, and controlling salt build-up. In the case of purge streams, the design should be in such a way that the level of impurities will not creep into a regime where spontaneous precipitation or scaling might occur. This issue is intensified where the project aims at achieving high water recycling to minimize freshwater demand, since the closed-loop operation can cause concentration of problematic ions. The domain perspective re-enters the picture: ore having higher inherent halides,

sulfate, or alkaline earth metals draws tighter restrictions on recycle ratios, except when, by pre-design, the results of complementary treatment and purge measures are intended to be implemented [69].

4.7. Variability Management and Geometallurgical Control as Operational Necessities

One last problem that cuts across the unit operations is variability. The deposits of alumina are usually highly spatially variable in terms of the types of clay and their degree of weathering, the percentage of impurities, and lithium deportment, and these changes can be transformed into alterations in slurry behavior and chemistry, resulting in plant upsets that are frequent unless controlled [18]. In contrast to other hard-rock systems, where mixing can be used to stabilize grade and mineralogy to a reasonable degree, clay-rich systems can be nonlinear, with small changes in reactive silica or fines fraction causing large changes in the viscosity or the filtration behavior. This renders variability management an operational requirement as opposed to an optimization process.

The mechanism to control variability using geometallurgical control is to relate mine planning, blending, and process set points to domain indicators [70]. Practically, this demands that domains should be characterized by quantities that can be tracked at a sufficient frequency and which are related to the limiting characteristics of the plant, such as gel propensity, acid consumption, set rate, and impurity release curve. Through these indicators, the operations can make changes in the severity of leaching, flocculation regimes, residence times, purge rates, or even the choice of routes of the various ore blends. In the absence of such integration, even well-designed flowsheets might not work well since they are exercised beyond their stable envelope as the characteristics of ore vary.

To sum up, critical technical issues in the alumina-rich lithium processing are all about the control of the aluminum and silica behavior, the solid-liquid separation is still workable, the deportment of the impurities is managed in a manner that safeguards the product specification, and the reliability is ensured under the recycle water drift and varying ore [71]. The control issues can be used to tell whether a processing route is only chemically feasible or can be really operable and scalable. Section 5 develops these realities by incorporating sustainability and techno-economic aspects and demonstrates that the same control points that define operability are the ones that define environmental hotspots, the presence of residue, and how closed-loop water and reagent approaches can work.

5. Sustainability and Techno-Economic Integration for Domain-Aware Decisions

In the alumina-rich lithium ores, sustainability and techno-economic performance cannot be separated since the same factors that pose threats to operability (i.e., high reagent demand, unstable solid-liquid separation, and large volumes of residues) also control the environmental footprint and costs [72]. The final constraints, especially the inherent recoverability of the lithium, are not the decisive ones in most projects, but rather the water balance, the carbon intensity of the heat and the electricity, the practicability of the salt and impurity buildup in closed circuits, and the long-term risks and liabilities of residue storage. An approach that is domain-aware is necessary; therefore, it permits sustainability and cost to be addressed as foreseeable consequences of ore properties and route choice, as opposed to downstream evaluation that is done when a flowsheet has already been selected. Section 5 is a synthesis of these considerations in that the key life-cycle and cost drivers of each route family are identified, the amplification or reduction of these drivers by the ore domains is explained, and how the closed-loop strategies and residue planning can be incorporated in the process design.

5.1. Environmental and Cost Hotspots across Flowsheet Families

In the lithium processing paths containing a significant amount of alumina, there are usually a small number of hotspots that control the environmental impact and the cost of operation. Thermal energy demand is frequently the most significant contributor to greenhouse gases and cost variability where roasting or high-temperature activation is needed, and it is also significant even in so-called wet flowsheets where leaching is actually done at elevated temperatures and where large volumes of slurry are required to be heated. The intensity of chemical reagent use,

especially acid or caustic, and downstream neutralizing agents often rivals power as the main operating cost element, and has concealed emissions of reagent production and transportation. Where there is an arid environment or where site hydrology limits the discharge, the water demand and water management infrastructure can dominate, and further energy penalties are imposed where the water is to be treated, pumped, or recycled at high rates. Lastly, a major cost center and major environmental and social risk can be the management of residue and tailings, especially in situations where the residue is voluminous, fine-grained, salty, or chemically reactive [73].

Hotspots are relatively significant depending on the route family. Direct acid leaching is inclined to redistribute the load to reagents and product formation since extensive dissolution of aluminosilicates leads to acid usage and high neutralization and separation of impurities [43]. The shift in the burden of neutralization to energy and air emissions control, coupled with a potential decrease in downstream reagent requirement and residue volumes of neutralization are associated with the thermal activation routes. In cases where high ionic strength recycles loops or desilication steps are needed, alkaline routes or hybrid routes could shift the burdens to salt management and water treatment. Selective extraction concepts have the potential of decreasing the burdens of reagents and residue when they do truly cause the limiting dissolution of gangue, yet their performance is also limited by the longevity and regeneration needs of the selective media and the proportion to which upstream conditioning remains based on the strength of the chemical.

Since these hotspots are traded off and not moved as a unit, sustainability is not that which can be deduced by looking at a single variable like lithium extraction. A path where energy requirements are minimized can maximize chemical footprint and a path where chemical addition requirements are minimized can maximize energy requirement [74]. The importance of domain-aware integration is that it can help understand when these tradeoffs are structural, requiring changes in the character of ore and are impossible to remove with relatively simple process modifications, and when they are contingent, and can be addressed through control strategies, heat integration, or reagent recycling.

5.2. Coupling Geometallurgy with Techno-Economic Analysis (TEA) and Life-Cycle Assessment (LCA): Domains as Predictors of Cost and Impact

The lithium projects are frequently expected to be studied using techno-economic analysis and life-cycle assessment as post hoc designs, but, in the case of alumina-rich ores, they are more effective design tools when combined with domaining [75]. The predictive inputs given by the ore domains are highly effective in the determination of capital and operating expenditures and the environmental impacts. As an illustration, domains that have a high potential for acid consumption and a high dissolution of aluminum will be more inclined to have a high operating cost because of reagents and neutralization, larger volumes of residue, increased water consumption because of dilution and washing, and increased embedded emissions related to chemical supply chains. Domains that are characterized by high gel propensity will be characterized by larger capital intensity as a result of oversized thickeners and filtration capacity, increased energy consumption as a result of reduced achievable pulp densities, increased pumping and mixing requirements, and increased complexity in managing water. Areas that must be activated to release lithium will shift the analysis towards the cost of the energy source, the intensity of carbon content of the heat source, and the success of heat recovery.

A domain-constrained TEA thus views consumption and operability measurements as economic forces, rather than as process measurements. Parameters of acid or caustic consumption, solid-liquid separation indices, and impurity discharge profiles may be converted into the cost of reagents, equipment sizing parameters, and maintenance overheads. Similarly, an environmental driver of a domain-conscious LCA uses these same indicators as drivers of the environment: reagent consumption is used to map to upstream emissions and potential aquatic impacts; the energy demand is used to map to greenhouse gas emissions and air pollutants, water balance is used to map to local water stress and treatment burden; and the residue volumes and chemistry are used to map to long-term risk and land use footprint [76].

Comparability and transparency are also enhanced in this coupling. Most sustainability claims do not work

as they compare routes with unequal boundaries or neglect the most significant aspects, like the production of reagents, residue management, or water treatment. A domain-conscious structure imposes the system boundary to create the most domain-sensitive processes, in particular, neutralization residues, recycling loops, and tailings dewatering. It also facilitates sensitivity analysis, which in fact is meaningful to the alumina-rich ores where minor changes in domain composition can substantially alter the reagent requirement and the filtration performance. Practically, it implies that the evaluation of the project must focus on domain-specific conditions as opposed to average-feed conditions, as worst-performing domains are usually what determine plant operability and risk.

5.3. Water Strategy and Closed-Loop Operation: Recycle Benefits and Salt Constraints

The critical sustainability factor of alumina-rich lithium projects, especially in arid areas or where discharge is limited, is often that of water management [77]. Clay ores are likely to demand more water due to the high viscosity of the slurry, low settling, and extensive washing to extract soluble lithium and minimize losses during entrainment. These water requirements provide a compelling incentive towards closed-loop operation and high recycle ratios, but these closed loops also present a countering limitation: salts and other impurities build up, altering water chemistry in a manner that may lead to the destabilization of the process.

Recycle chemistry in alumina-based systems influences dispersion and flocculation of clays, modifies the equilibrium of precipitation between aluminum and silica, and may exacerbate scaling and corrosion [78]. Practically, a flowsheet designed for fresh water may enter a new operating regime when under recycle, where the gelation thresholds are violated earlier, the flocculants do not act as they do, and the product crystallization process becomes more difficult to control. It is due to this fact that sustainable water strategies should be formulated based on steady-state recycle chemistry as opposed to initial conditions. This involves a clear definition of purge streams, treatment stages, and make-up water requirements, and an appreciation that there are areas that have more restrictive recycle requirements due to higher loads of halide or sulfate, higher loads of alkaline earth metals, or higher loads of dissolved silica and aluminum.

Tradeoffs also differ in their interpretation by a domain-aware water strategy. High recycling lowers freshwater demand and has the potential to lower the amount discharged, but it may also lead to the growth of energy consumption related to pumping and treatment and may also result in increased chemical consumption to counteract deterioration of performance related to separation. There are also situations when a moderate recycle strategy with a well-developed purge and treatment system could be more sustainable compared to an aggressive recycle strategy which leads to instability and regular shutdowns. The sustainable optimum is thus the sustainable option that maintains operability and residue stability and has minimized net water withdrawal and salt balances, which are transparently handled [46].

5.4. Residue and Tailings Management as a Primary Sustainability Design Variable

Production of residues in the alumina-rich lithium processing may be significant compared with the mass of lithium product, and the nature of the residue usually dictates environmental hazard and its ultimate cost [54]. The residues may consist of leached solids, neutralization precipitates, desilication products, and other salt-bearing streams whose management may be combined or individual. Clays and fine particles have a strong influence on their physical behavior and may result in high non-permeability, slow consolidation, and difficulty in realization of high-density disposal. Their chemistry is affected by the process reagents and the natural impurity suite of ore, which may create high salinity, stagnant acidity or alkalinity, and in certain instances, releasable constituents, which must be carefully classified and confined.

Sustainable residue management starts with a design-to-closure mentality whereby the shape and chemistry of residue is determined by upstream decisions. Gangue dissolution minimizing routes are likely to produce smaller amounts of neutralization precipitates and may decrease the amounts of dissolved salt, leading to enhanced long-term residue stability and fewer water-treatment requirements. Roads based on aggressive breakage and eventual neutralization, on the contrary, produce large masses of fine precipitates and salty loads, multiplying footprint and closure risk. Thermal activation methods can be used to eliminate neu-

tralization residues but can form soluble salts that need to be carefully handled in terms of water, and can change mineral phases that can change the reactivity of the residues [79].

Residue risk is not homogeneous, as it regards a domain. Areas where the inputs of sulfates or chloride are high can result in residues of the salinity that is higher and drives seepage issues and necessitates more conservative lining as well as water collection systems. Areas that have large fines and a gel-prone nature may result in having a difficult time dry stacking without high filtration ability and conditioning, and predispose to dusting should the residues be dried without uniformity. Due to tailings storage being a core area of concern in social license, the projects, which use alumina-rich ores, should also demonstrate how residues can be dewatered, stored, monitored, and closed safely in credible worst-case conditions of the domain, rather than in average ones [80].

5.5. Valorization and Circularity: Opportunities and Realism for Aluminosilicate Residues

Residues rich in aluminosilicates are open to the concepts of circularity since they can be used as feedstocks to obtain construction materials, geopolymers, zeolites, or other industrial products [81]. Valorization in terms of sustainability can minimize disposal quantities, generate sources of revenue, and even offset emissions in case the residues are used in conjunction with alternatives to more carbon-intensive materials. Nevertheless, in the case of lithium projects that are rich in alumina, the valorization of the residues should be approached with a certain degree of realism. Marketability can be harshly disrupted by the chemical variability of residues, salts, and trace contaminants, as well as the necessity to fulfill product requirements and regulatory standards. Moreover, valorization pathways may involve extra processing, energy, and binders, which may destroy net environmental advantages unless they are assessed transparently.

A domain-biased strategy is useful once again as it can find out which residues are the most probable to be valorized. The milder conditions in lower-salinity, more uniform mineralogy produce fewer residues to justify industrial use of such residues than those of either neutralization sludges or high-salt streams. In an attractive case, even the size of the possible market is a practical limitation: lithium projects can produce volumes of residues for any one product that can meet the local demand. Thus, valorization can be discussed as a set of partial outlets instead of one outlet**,** which will remove tailings. Residue stability and safe storage must be considered as the minimum requirement of sustainable planning, and valorization needs to be pursued as long as it is technically plausible, environmentally profitable on a life-cycle basis, and has market and permitting pathways [80,82].

5.6. Reporting, Comparability, and Decision Readiness: What “Sustainable” Must Include

In the case of lithium ores that contain alumina, their sustainability arguments are only as good as the reporting procedures underpinning them [83]. Inter-route and inter-study comparisons are usually unsatisfactory as they exclude such important burdens as neutralization residues, water treatment, or dewatering energy, or fail to mark the reported consumption levels by either fresh water or steady-state condition of recycling. Decision-ready reporting should hence comprise transparent mass balances that encompass lithium losses to residues, and it should also disclose reagent utilization and energy requirements per a steady functional unit of 1 ton of lithium carbonate equivalent. It should also comprise residue characterization adequate to determine the risk of long-term storage, such as salinity, leachability, and physical properties that influence consolidation and seepage. In the absence of such data, one cannot say whether a seemingly effective laboratory process can be reflected in the sustainable flowsheet of industrial processes.

It is possible to combine TEA and LCA with domaining to enhance the quality of reporting by making the variability clear and forcing sensitivity analysis focused on the key parameters of alumina-rich systems [84]. Instead of giving one number as the headline figure of recovery, cost or carbon intensity, domain-sensitive measurements give ranges as a result of ore variability and also point out the limits that characterize the operating envelope of feasibility. This is the developmental pattern that is consistent with the real process of developing and authorizing projects since the regulators, investors, and communities may be worried not only about the average but also about risk, dependability, and closure performance under the condi-

tion of realistic variability. In order to make sure that the sustainability claims are comparable and decision-enabled, it will be necessary to include performance metrics that go beyond lithium recovery and encompass energy, water, reagent, and residue performance. **Table 4** contains a useful checklist of suggested reporting items recommended to combine techno-economic and life-cycle considerations on the ore-domain variability.

Table 4. Sustainability and TEA/LCA integration recommended metrics.

Category	Recommended Metric/Reporting Item	Notes for Alumina-Rich Ores (Why This Is Load-Bearing)
Functional unit and boundary	Report per tonne Li_2CO_3-equivalent (or LiOH) with clear system boundary	Comparability requires consistent boundaries including residue and water treatment
Energy and carbon	Thermal energy (GJ/t Lithium Carbonate Equivalent (LCE)) and electricity (MWh/t LCE); carbon intensity by energy source	Activation routes shift hotspots to heat; leaching at high S/L affects heating duty
Reagents	Acid/alkali and neutralizing agents (kg/t LCE) with consumption basis and recycle assumptions	Gangue dissolution dominates; must distinguish fresh-water tests vs. steady-state recycle
Water	Net freshwater withdrawal; recycle ratio; purge rate; key ion buildup trends	Closed-loop operation can shift rheology/precipitation equilibria; salt balance is central
Residues/tailings	Mass of residue per t LCE; salinity indicators; dewatering method; storage concept	Residue volumes can dominate footprint; closure risk must be demonstrable
Product quality	Final impurity profile vs. specification; yield losses by purification step	Co-precipitation/entrainment losses can be hidden without stepwise mass balance
Variability	Domain-based ranges (best/typical/worst) for the above metrics	"Average ore" can be misleading; worst domains often control design and risk

Overall, it can be concluded that it is a small group of non-renewable and interconnected drivers: energy, reagents, water, and residues, which, in effect, are the domain of the ores and the choice of routes that characterize the sustainability and technogenic features of the process of lithium production from no less alumina-metallic ores. A sustainable pathway will produce lithium recovery, good product quality, and have consistent operation in a closed loop, limit chemical intensity and risk of residues, and ensure closure planning is integrated with design. Such lessons encourage the final conclusion of Section 6, in which the principles of best practice and the priorities of future research can be condensed into a prospective roadmap of scalable, alumina-based lithium utilization with environmental sustainability requirements of Environmental, Social, and Governance (ESG).

6. Conclusion and Future Outlook

Sustainable exploitation of lithium in the alumina-rich ores requires accepting that these feedstocks are essentially geometallurgical systems, and not homogeneous feedstocks. Compared to traditional brines and spodumene concentrates, lithium is usually present in alumina-rich ores as fine-grained aluminosilicates that determine both lithium release and dissolution of both alumina and silica, formation of gelation and rheology issues, as well as the scale and chemistry of residues formed. In the literature, the most consistent conclusion has been the fact that bulk lithium grade is not a strong indicator of technical viability as well as sustainability. These include lithium deportment, aluminosilicate and silica reactivity, fines behavior, and impurity suites, as the two predominant determinants that influence the complexity of purification and the possibility of operating on closed-loop water.

A domain-knowledge scheme offers a viable route to utilize this variability into robust changes in viable selection. Where lithium is comparatively available and is not widely dispersed through the matrix, the ideas of selective extraction and gentler leaching options are technically and ecologically appealing since they restrict the mobilization of aluminum and silica and diminish the need to create neutralizing agents, as well as reduce the amount of residue produced. In systems where there is a structural constraint of lithium and the liberation of the lithium cannot be decoupled from the disruption of the framework, thermal activation or step-by-step hybrid strategies may provide a viable route by decoupling the lithium recovery and uncontrollable disruption of the gangue, although at the penalty of increased energy requirements and inevitable emissions. The gel propensity and strong buffering capacity, the high levels of alkaline earths, or the high levels of halide/sulfate loads also put further constraints on the routes which are possible at any rate, particularly when realistic pulp den-

sities and steady-state recycle water chemistry are used. Domaining in this sense is not simply an exercise of characterization, but a form of decision logic which ensures flowsheets do not optimize to behave in the laboratory but fail when put in the industrial environment.

Another important point made in the review is that in alumina-rich systems, operability and sustainability are closely intertwined. Not only are aluminum dissolution and silica polymerization chemical obstacles, but they also cause water demand, separation capacity, reagent intensity, and volume, as well as long-term risk of residues. Similarly, water, particularly the drive to recycle water, which is one of the key sustainability goals, can add to salt and clay deposits, altering the behavior of clay dispersion and increasing the risk of scaling or gelation, unless purge, treatment, and circuit chemistry are specified. The management of the residue and tailings cannot thus be handled as a secondary design variable, and the principles of design to closure need to be incorporated into the route choice, reagent design, and solid–liquid separation decisions. Circularity can somehow be supported through valorization of aluminosilicate residues, but only in certain situations, and only as an addition, not an alternative to, careful storage and closure planning.

In the future, some priorities become apparent to scale ESG-prepared lithium production out of lithium-rich alumina ores. In the first place, the field should be provided with standardized, domain-relevant reporting comprising quantitative mineralogy, characterization of particle size and fines, lithium and impurity deportment, complete mass balances, considerations of steady-state recycle water, and residue properties associated with long-term stability. Second, selectivity, as recovering lithium and reducing the dissolution of aluminum and silica, should be maximized by innovating selective activation, shut windows, and powerful selective separations that are still effective in complex liquors. Third, electrification of energy-intensive processes, such as electrified or even low-carbon heat, and increased heat integration where activation is necessary, will be necessary. Fourth, the water and salt management solutions should be prepared and tested in the conditions of closed circuits under realistic conditions, and the design of the purges, treatment alternatives, and scaling regulation should be described. Lastly, residue failure and possible valorization ought to be addressed along with regulatory and market reality, with a focus on being consistently securable and verifiably life-cycle advantageous.

Overall, lithium ores with high alumina content have the potential to play an important role in the future of lithium, although, because of the generic flowsheet approach, they cannot be developed sustainably without transitioning to a geometallurgy-based paradigm where the domains of ore determine the viable processing window and the sustainability profile. The strongest pathways will be the ones that relate deposit knowledge and domain classification with flowsheet design to closed-loop resource management and responsible residue outcomes. Through the use of domain-sensitive decision models and enhanced comparability via standardized data sets, the community will be able to speed up the process of moving out of the laboratory demonstrations to trustworthy industrial practice that fulfills economic and environmental demands.

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