

Intellectual Property, Innovation and Patent-Based Technological Prospecting for Critical Minerals: Mapping Lithium and Niobium Mining and Extractive Metallurgy Technologies

Izaias Dantas Lima, Irla Maria Santos Pereira, Isadora Almeida Lino Vieira,
Gustavo Pereira da Cruz

Economist and Master's Student in PROFNIT at Santa Cruz State University – UESC

Undergraduate Student and Teaching Assistant at DCAC at Santa Cruz State University – UESC

Advertising Graduate at UNIFACS and Graduate Student in Cultural Management at Santa Cruz State
University – UESC³

PhD Researcher and Professor at DCAC and PROFNIT at Santa Cruz State University – UESC⁴

ABSTRACT: The transition to a low-carbon economy intensifies the global demand for critical minerals such as lithium and niobium, which are essential for clean energy technologies. This study aims to apply a technological prospection methodological roadmap, based on patent document analysis, to map innovation in exploration and extractive metallurgy technologies for these minerals, identifying technology transfer opportunities for the Brazilian mineral sector. Methodologically, an exploratory and quantitative research was conducted in the Espacenet database (2015–2025), using a hybrid search strategy that combined sectoral vocabulary and Cooperative Patent Classification (CPC) codes, resulting in a corpus of 980 patent families. The results show accelerated growth in inventive activity starting in 2023 and a marked hegemony of Chinese research institutions in developing chemical and sustainable routes. It is concluded that there is a geographical gap between the location of reserves and technological domain, highlighting the urgency of licensing strategies and international cooperation for the internalization of technological capabilities in Brazil.

KEYWORDS: Critical Minerals. Technological Prospection. Patents. Lithium. Niobium.

I. INTRODUCTION

The transition towards a low-carbon economy, driven by the Paris Agreement and the targets established under the United Nations 2030 Agenda, has substantially accelerated global demand for critical minerals, which have become essential raw materials for clean energy technologies such as photovoltaic systems, wind turbines, electric vehicles and advanced energy storage solutions (Santos, 2023; WEF, 2024). In this context, minerals previously considered sector-specific inputs have acquired strategic relevance because of their direct contribution to industrial decarbonisation, energy security and technological sovereignty.

Among these resources, lithium and niobium occupy particularly prominent positions owing to their role in enabling technologies associated with the global energy transition. Lithium has become indispensable for lithium-ion batteries used in electric mobility, stationary storage systems, defence applications and aerospace technologies (IBRAM, 2025; BRASIL, 2010). Recent projections indicate sustained growth in global demand over the coming decades, reflecting both accelerated electrification and the expansion of battery-intensive industrial sectors.

Recent reports produced by Instituto Brasileiro de Mineração and Brazilian federal agencies indicate that lithium currently represents one of the principal drivers of growth in transition mineral demand (IBRAM, 2023). In parallel, Brazil has strengthened its international relevance through projects capable of producing battery-grade lithium

compounds under environmentally differentiated production standards, frequently referred to as “green lithium”, increasingly valued in regulated international markets (BRASIL, 2011).

In the case of niobium, Brazil occupies an even more distinctive position. The country holds the majority of known economically exploitable reserves and remains the leading global producer of niobium oxides and ferroniobium alloys (USGS, 2024). Beyond conventional metallurgical applications, niobium has progressively entered frontier technological domains, including advanced alloys, aerospace materials and battery components. Recent technological developments involving niobium-based anodes for ultra-fast charging batteries indicate growing opportunities for this mineral in advanced energy storage systems (CBMM, 2023).

These strategic conditions have led Brazilian policy instruments, including the National Mining Plan 2050, to classify both lithium and niobium as priority minerals for industrial development, insertion into global value chains and fulfilment of international climate commitments (Brasil, 2024). However, geological abundance alone does not guarantee technological competitiveness. Contemporary value capture increasingly depends on the ability to control technological stages beyond extraction, including mineral processing, separation technologies, refining and advanced material development (Moura Jr.; Racy, 2018; BRASIL, 2010).

Recent literature on the extractive mineral industry highlights that competitiveness increasingly depends on the incorporation of more efficient technologies while simultaneously reducing environmental impacts and improving process intelligence (Daly; Valacchi; Raffo, 2019). Policy documents further indicate that Brazil must prioritise technological upgrading through shared infrastructure, digitalisation, automation and artificial intelligence, especially in sectors where productivity and sustainability increasingly converge (MME, 2024).

Innovation in the mineral sector, however, is not restricted to large mining corporations. Relevant technological advances increasingly emerge from a broader ecosystem involving Mining Equipment, Technology and Services (METS) firms, start-ups, engineering suppliers, specialised service providers and collaborations with Science and Technology Institutions (ICTs) (Daly; Valacchi; Raffo, 2019). These actors frequently operate through flexible production systems, open innovation models and pre-competitive cooperation structures, contributing to technological diversification and reducing uncertainty associated with high-risk industrial investments. Within this ecosystem, technology transfer assumes particular strategic relevance as a mechanism for accelerating technological absorption, strengthening productive capabilities and expanding industrial cooperation (BRASIL, 2011).

In this regard, technological prospecting based on patent documents constitutes an important analytical instrument for mapping innovative effort, identifying dominant technological actors and locating opportunities for future cooperation (Quintella et al., 2011). Patent databases provide structured information on technological development trajectories, allowing systematic analysis of inventive activity through publication trends, applicants, technological classifications and jurisdictional strategies (Paranhos, 2019).

Against this background, the present study addresses the following research question: how can patent-based technological prospecting contribute to mapping innovation trajectories in extraction, mineral processing and extractive metallurgy technologies associated with lithium and niobium, while also indicating technological actors and opportunities relevant to technology transfer within the Brazilian mineral sector?

Accordingly, the objective of this article is to apply a patent-based technological prospecting framework to identify recent innovation patterns in technologies related to lithium and niobium mining, mineral processing and extractive metallurgy during the period 2015–2025, with particular emphasis on temporal evolution, technological concentration, applicant profiles, geographical distribution and predominant technological classifications. Based on these indicators, the study also seeks to identify actors with potential relevance for future cooperation and technology transfer strategies within the Brazilian mineral innovation ecosystem.

The relevance of this research lies in addressing an important analytical gap concerning technological intelligence in strategic mineral sectors. Although Brazil holds internationally significant reserves and productive capacity in both minerals, limited systematised evidence remains available regarding who is patenting, in which technological domains innovation is concentrated, and how these patterns may inform industrial policy and institutional cooperation. From a practical perspective, the findings may support Science and Technology Institutions, Technology Transfer Offices,

mining companies, METS firms and public policy actors in identifying technological trajectories, potential industrial partners and strategic domains for capability building.

The article is structured as follows. Section 2 discusses the strategic relevance of lithium and niobium within the broader framework of critical minerals and examines Brazil's position in international mineral value chains. Section 3 presents the theoretical foundations of patent-based technological prospecting and its application to mineral technologies. Section 4 describes the methodological procedures adopted. Section 5 presents and discusses the results of the patent landscape analysis, and Section 6 outlines the main conclusions and implications for future technology transfer strategies.

II. CRITICAL AND STRATEGIC MINERALS

The operational definition of which minerals are considered critical can vary depending on issues related to their use in specific cases, such as the energy transition, or on other market aspects such as their availability or substitutability (ADB, 2024). Organizations such as the International Energy Agency (IEA) and other institutions like the European Commission establish that criticality emerges from the confluence between high demand for low-carbon technologies or others related to strategic sectors and the risks of supply disruption arising from high global demand, geographic concentration of reserves, and even geopolitical issues (ADB, 2024; European Commission, 2023). Within the Brazilian academic and regulatory context, an important distinction is established between criticality, generally associated with external supply risks and import dependence, and strategic relevance, which reflects reserve abundance and long-term productive potential for internal technological development (WEF, 2024; IBRAM, 2025).

2.1 Importance of Lithium and Niobium and Brazil's Position in the International Context

Lithium has become a central pillar of global decarbonisation due to its irreplaceable application in batteries for electric vehicles and stationary storage systems. Current projections indicate an unprecedented expansion scenario, with demand potentially increasing 8.6-fold by 2030 and reaching levels equivalent to sixteen times 2022 consumption by 2040 under net-zero emission scenarios (ADB, 2024).

Although urban mining and recycling strategies are considered promising, current limitations associated with end-of-life battery availability indicate that recycling will cover only part of future demand, making substantial expansion of primary extraction unavoidable (ADB, 2024).

Unlike lithium, whose market is characterised by supply vulnerability and geopolitical competition, niobium represents a strategic mineral under strong Brazilian geological dominance. Brazil holds approximately 98% of known economically exploitable reserves and accounts for over 90% of global primary production (WEF, 2024).

Applications of niobium have expanded considerably beyond traditional steelmaking and superalloys used in aerospace and defence sectors. Significant investments in research and innovation, particularly by Companhia Brasileira de Metalurgia e Mineração, have enabled technological advances in special oxides and niobium-based battery materials (IBRAM, 2025; WIPO, 2019). The accelerated transition towards low-carbon energy systems has intensified global competition for secure supply of minerals such as nickel, cobalt, graphite, rare earth elements and lithium, increasing disputes over technological and commercial value capture (ADB, 2024; WEF, 2024).

This new industrial context reveals that competitive advantage does not derive solely from extraction capacity, but increasingly from control over refining, precursor synthesis and specialised component manufacturing. Historically centred on exporting raw mineral commodities, Brazil now faces the strategic challenge of converting geological advantage into industrial leadership through technological densification across mineral value chains.

III. PATENT-BASED TECHNOLOGICAL PROSPECTING

Technological prospecting comprises a set of methods and analytical tools designed to systematically identify technological development trajectories within specific fields, supporting strategic decisions in research and development, industrial policy and intellectual property management (WIPO, 2015). Among available instruments, patent mapping is particularly relevant because it enables identification of innovation trends, dominant actors,

technological gaps and potential technology transfer opportunities through bibliographic and textual analysis of patent documents (Firat et al., 2008; Santos et al., 2004).

Patent mapping is especially valued because it combines broad international coverage with temporal traceability. Global databases such as European Patent Office/Espacenet, United States Patent and Trademark Office and World Intellectual Property Organization allow monitoring of patent families, applicants, inventors and technological evolution across jurisdictions (Pires; Ribeiro; Quintella, 2020; Paranhos, 2019).

The principal stages of patent-based technological prospecting generally include scope definition, search strategy design, data cleaning, grouping by patent families and descriptive analysis of technological indicators. Patent analysis typically examines temporal evolution of filings, applicant concentration, geographical distribution and technological classification patterns through CPC and IPC systems. Citation analysis may additionally identify influential inventions and emerging technological trajectories (WIPO, 2015; Smith, 2018). Its particular relevance for critical minerals lies in the fact that patent documents reveal dimensions of technological competition not fully captured by scientific publications, especially where industrial appropriation and strategic positioning strongly influence innovation dynamics (Daly; Valacchi; Raffo, 2019).

In sectors such as lithium and niobium mining, where processing technologies often determine value capture more decisively than extraction itself, patent analysis offers an especially useful lens for understanding technological concentration, identifying dominant actors and recognising underexplored technological spaces that may support future cooperation or innovation strategies.

IV. METHODOLOGY

4.1 Research design and database selection

This study is characterised as an exploratory and descriptive quantitative investigation based on patent document analysis in specific technological domains, with the objective of identifying technological development trends, dominant innovation actors, and opportunities for technology transfer within the critical minerals sector.

The empirical database used was European Patent Office's Espacenet, which provides free access to more than 200 million patent documents filed worldwide (EPO, 2025). The selection of Espacenet was justified by three main factors.

First, its broad international coverage enables access to patent filings across multiple jurisdictions, which is essential when analysing globally distributed technological trajectories. Second, its free accessibility allows methodological replication by university-based Technology Transfer Offices (TTOs), public innovation agencies and researchers operating under limited financial resources. Third, the platform allows the construction of advanced search strings combining keywords, Cooperative Patent Classification (CPC) codes and Boolean operators, in line with methodological recommendations established in international patent landscape studies. This combination is particularly relevant in mining-related technological domains, where lexical ambiguity frequently compromises search precision (Smith, 2018; Van Rijn; Timmis, 2023).

4.2 Methodological framework adopted

Based on international guidelines for patent landscape reporting developed by World Intellectual Property Organization (WIPO, 2015), sectoral studies on mining innovation, and recent methodological contributions in patent analytics (Daly; Valacchi; Raffo, 2019; van Rijn; Timmis, 2023), a four-stage analytical framework was adopted:

- (i) scope planning and technological delimitation;
- (ii) search strategy construction and data retrieval;
- (iii) data cleaning and normalisation;
- (iv) patent indicator analysis.

This framework was designed to ensure analytical consistency between search construction and interpretation of technological patterns observed in lithium and niobium mining-related innovation. The four stages are described below as applied to the specific case of critical mineral extraction and processing technologies.

4.3 Phase 1: Scope planning and technological delimitation

The technological scope of this patent prospecting exercise covered mining, drilling, crushing, grinding, classification and mineral concentration technologies, as well as extractive metallurgical processes associated with lithium and niobium production.

The inclusion of beneficiation and extractive metallurgy was considered essential because, for critical minerals associated with low-grade deposits, the principal frontier of patentable innovation increasingly lies in chemical separation and purification processes rather than in ore extraction itself. The analytical focus was restricted to two critical minerals (lithium and niobium) whose strategic relevance has grown substantially in the context of the energy transition, electrification and advanced industrial applications. The temporal scope was defined as 2015–2025 in order to capture the most recent cycle of accelerated demand expansion associated with battery production, energy storage systems and strategic alloys.

To define the innovation ecosystem (Daly; Valacchi; Raffo, 2019), the study adopted the premise that innovation in mining does not emerge exclusively from mining corporations, but also strongly from specialised suppliers of equipment, process technologies and technical services, commonly classified as Mining Equipment, Technology and Services (METS).

Accordingly, applicant analysis was structured to distinguish mining firms, METS companies, universities, public research institutes and other organisational actors. This classification later supported interpretation of technological ownership patterns observed in the patent dataset.

4.4 Phase 2: Search strategy and iterative refinement process

The search strategy was developed through an iterative process of testing, validation and refinement, following international patent landscaping recommendations (van Rijn; Timmis, 2023).

Initial exploratory search (Query 1): The first exploratory query relied exclusively on unrestricted vocabulary, without classification filters: "Mining" AND (ti = "niobium" OR ab = "lithium)". This query returned 5,529 patent documents (search conducted on 8 March 2026, filtered for 2015–2025).

A qualitative inspection of the first 50 retrieved records revealed substantial noise. Most false positives were associated with battery technologies, electromobility applications, text mining, data mining and non-mineral uses of the term mining.

A strong imbalance between lithium-related and niobium-related documents was also observed, largely because no CPC filters had yet been introduced to isolate mining-related technologies. These results empirically confirmed a well-documented methodological challenge in mineral patent analysis: mining-related terminology suffers from severe lexical ambiguity (Daly; Valacchi; Raffo, 2019). Terms such as mining, stripping and lithium frequently appear in unrelated technological sectors, substantially reducing precision when free vocabulary alone is used. Refined search strategy (Query 2): Based on the diagnostic limitations of Query 1, a hybrid strategy combining three filtering mechanisms was developed.

Block 1 – Mining-related technological terms and CPC classes

Mining sector vocabulary in title and abstract fields (mineral, mining, ore, metallurgy) combined with CPC classes:

- E21C — Mining and extraction
- E21B — Drilling
- B02C — Crushing and grinding
- B03B — Separation and classification
- B03D — Flotation and concentration
- C22B — Extractive metallurgy (including hydrometallurgy and pyrometallurgy)

Block 2 – Critical mineral descriptors

Lithium and niobium terms in title and abstract fields.

Block 3 – Exclusion dictionary

Negative operators excluding adjacent sectors:

- coal
- petroleum
- oil
- weapon
- data mining

The final search expression applied in Espacenet was: “(((ti = "mineral*" OR ti = "mining" OR ti = "ore" OR ti = "metallurgy" OR ab = "mineral*" OR ab = "mining" OR ab = "ore" OR ab = "metallurgy")) AND (cpc = "E21C" OR cpc = "E21B" OR cpc = "B02C" OR cpc = "B03B" OR cpc = "B03D" OR cpc = "C22B")) AND (ti = "lithium" OR ti = "niobium" OR ab = "lithium" OR ab = "niobium")) NOT (ti = "coal" OR ti = "petroleum" OR ti = "oil" OR ti = "weapon" OR ti = "data mining" OR ab = "coal" OR ab = "petroleum" OR ab = "oil" OR ab = "weapon" OR ab = "data mining")”

The search was conducted on 8 March 2026 using the 2015–2025 temporal filter and returned 980 patent documents, which constituted the final analytical corpus. This refinement substantially increased precision and reduced false positives, producing a dataset aligned with the technological domains later observed in CPC distribution and applicant profiles.

4.5 Phase 3: Data cleaning and normalisation

The 980 records were exported in CSV format, containing:

- publication number
- patent family
- title
- applicant(s)
- country of origin
- CPC classes
- priority date
- publication date

The cleaning procedure involved three stages. First, records were grouped by patent family whenever family information was available, in order to avoid multiple counting of the same invention across jurisdictions. Second, a manual screening of titles and abstracts was performed to remove residual out-of-scope documents that remained after filtering. Third, applicant names were manually standardised to consolidate spelling variations, subsidiaries and affiliated entities belonging to the same organisational group. This normalisation was particularly important because many Chinese institutions and industrial groups appeared under multiple transliteration variants. The resulting cleaned dataset served as the basis for all subsequent statistical analyses.

4.6 Phase 4: Analytical indicators and technology transfer orientation

Applicant profiling was conducted through a dictionary-based classification technique.

Applicant names were normalised and automatically categorised as Universities/Research Institutes (ICTs) through root-word identification such as:

- univ
- inst
- academy

Mining firms and METS companies were classified through a nominal list based on major global corporations operating in mineral extraction and process technologies. Applicants not matching these criteria were initially classified as Others and subsequently reviewed manually. In addition to applicant profiling, the following analytical indicators were generated:

- temporal evolution of patent filings (2015–2025);
- identification of leading applicants, distinguishing mining firms from METS actors;
- geographical distribution by applicant country and first filing jurisdiction;

- most frequent CPC classes, indicating dominant technological routes;
- identification of key actors with potential relevance for technology transfer partnerships;
- degree of concentration versus dispersion of applicants across technological subfields, interpreted as an indicator of technological maturity and competitive intensity.

These indicators were selected because they allow simultaneous interpretation of technological dynamics and practical implications for innovation policy and technology transfer strategies, especially in mineral-producing countries seeking to strengthen domestic technological capabilities.

V. RESULTS

5.1 Temporal evolution of inventive activity (2015–2025)

The temporal evolution of patent filings provides important evidence regarding global Research and Development efforts directed towards lithium and niobium extraction and processing technologies. The distribution of the 980 patent families retrieved for the period 2015–2025 reveals a recent shift in the intensity of technological innovation in this field, as illustrated in Figure 1.

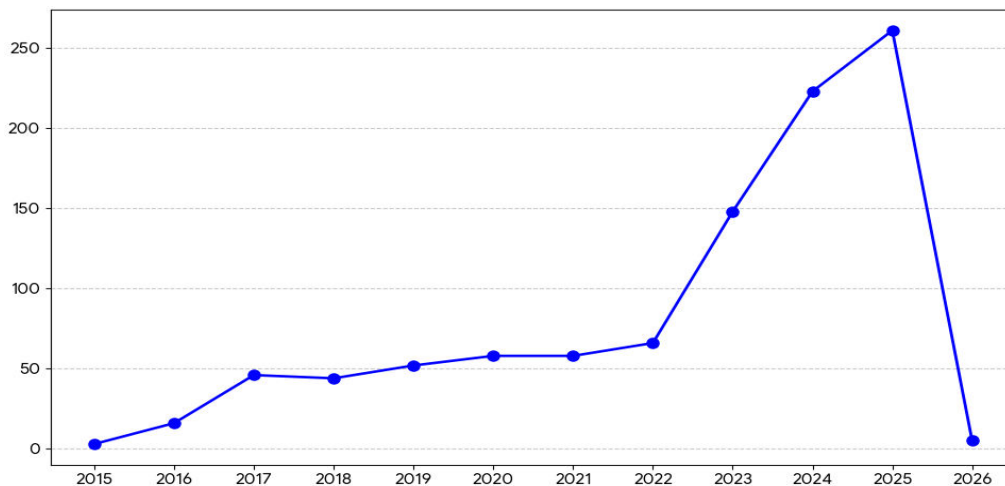


Figure 1 – Annual evolution in the number of patent families (2015–2025)

Source: Authors' own elaboration.

The data shown in Figure 1 indicate the existence of two distinct phases throughout the historical series. In the first phase, approximately between 2017 and 2022, patenting activity remains relatively stable, with annual volumes fluctuating between 50 and 70 patent families. This pattern is consistent with a technological regime characterised predominantly by incremental innovation, with limited structural change in the underlying technological landscape.

From 2023 onwards, however, a clear inflection point emerges. The number of published patent families rises sharply to 148 in 2023 and continues to expand significantly, reaching 223 in 2024 and 261 in 2025. This acceleration is consistent with the international phenomenon often described as the critical minerals boom, whereby rapidly growing demand for lithium and other strategic metals — driven by the expansion of electric mobility and large-scale energy storage systems — has intensified pressure on upstream mineral value chains. World Bank (2020) identifies this trend as a defining feature of the contemporary energy transition.

The concentration of patenting activity in 2024 and 2025, which together account for nearly half of all patent families identified in the sample, suggests that lithium and niobium beneficiation and extractive metallurgy have rapidly become one of the most dynamic technological frontiers of the global industrial transition, directly linked to decarbonisation strategies and energy security concerns.

More specifically, according to Instituto Brasileiro de Mineração (IBRAM, 2025), substantial investments in niobium-related R&D have generated an expanding diversity of industrial applications and enabled the emergence of advanced technological routes, including the recently established production of anodes for ultra-fast rechargeable lithium-ion batteries. This diversification contributes to reducing the strategic vulnerability traditionally associated with critical minerals.

In parallel, technological competition around lithium is increasingly shaped not only by primary extraction capacity, but also by the strategic need to dominate downstream chemical processing, particularly the production of oxides and hydroxides required by the rapidly expanding electric vehicle supply chain.

5.2 Technological landscape: metallurgical processes and sustainability

To characterise the technological nature of the protected inventions, the technological landscape was mapped through extraction and frequency analysis of Cooperative Patent Classification (CPC) codes associated with each patent family. This approach makes it possible to identify which technical routes are currently prioritised for industrial-scale extraction and processing of lithium and niobium. The most recurrent technological domains are summarised in Figure 2.

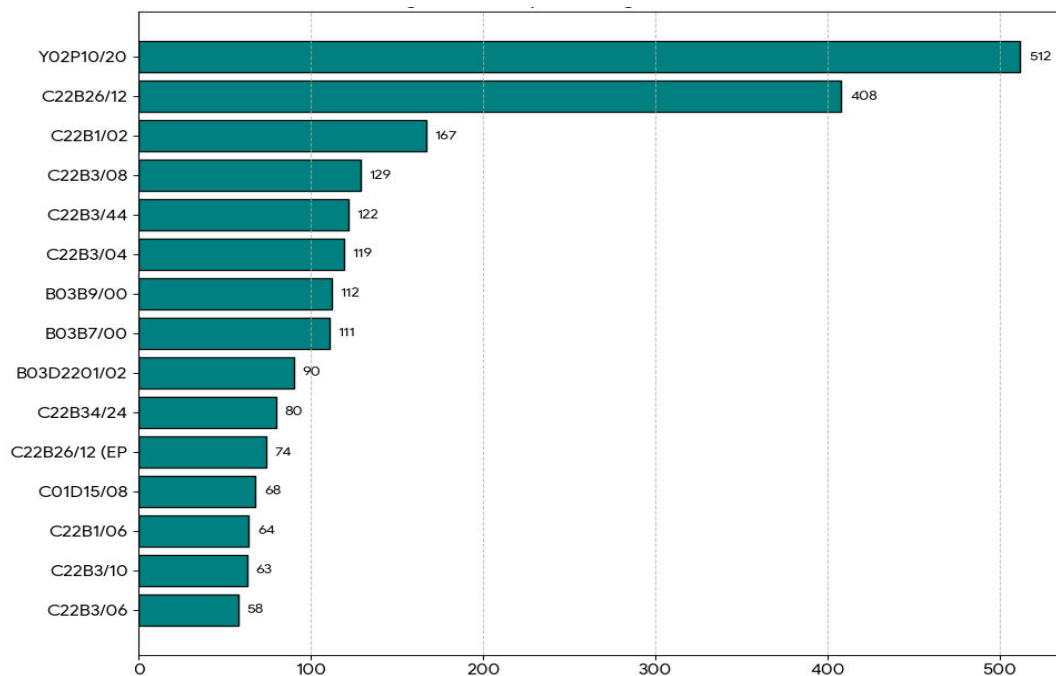


Figure 2 – Frequency distribution of CPC codes in the sample

Source: Authors’ own elaboration.

The results reveal three major technological axes structuring the current innovation landscape. The first concerns sustainability requirements, evidenced by the predominance of code Y02P10/20, associated with climate change mitigation technologies in metal production. The frequency of this code indicates that a substantial share of the inventions identified is embedded in environmental performance strategies, including greenhouse gas reduction and improved efficiency in the use of water and energy.

This finding suggests that technological development for lithium and niobium is increasingly conditioned by environmental constraints and by the incorporation of ESG criteria into mineral production systems. The second axis is directly related to extractive metallurgy, particularly class C22B (metal production and refining), which dominates the ranking of technological classifications. In addition to specific subclasses dedicated to lithium production (C22B26/12)

and niobium/tantalum recovery (C22B34/24), there is strong representation of roasting routes and other pyrometallurgical processes (C22B1/02), as well as hydrometallurgical approaches involving acid leaching, separation and purification stages (C22B3/08, C22B3/04, C22B3/44).

Taken together, these results reinforce the understanding that, for critical minerals extracted from low-grade deposits, the principal technological bottleneck lies less in mining operations themselves and more in the development of robust and economically viable chemical routes capable of separating valuable metals from increasingly complex ores.

This technological shift towards advanced metallurgical processing is strongly supported by sectoral literature, which identifies declining ore grades as one of the principal drivers of rising operational costs and energy intensity in primary mineral extraction (IBRAM, 2025; PwC, 2024). The third axis relates to physical beneficiation and the growing role of urban mining. Upstream from metallurgical processing, relevant codes indicate technological effort directed towards separation plant configurations, advanced flotation systems and mineral classification techniques aimed at improving pre-concentration efficiency.

Simultaneously, the presence of battery-related and recycling classifications, such as H01M10/54 and Y02W30/84, demonstrates that part of recent inventive activity is shifting from primary extraction towards lithium recovery from industrial residues and spent batteries, reflecting circular economy strategies.

Together, these three axes indicate that the technological landscape surrounding lithium and niobium increasingly combines environmental pressure, metallurgical sophistication and the expansion of extraction beyond conventional mining frontiers. The technological recovery of secondary materials from industrial scrap, process residues and post-consumer batteries substantially reduces the need for new mining operations, lowers energy demand and mitigates greenhouse gas emissions associated with primary beneficiation. An important regulatory example can be observed in Europe, where the European Parliament (2022) has strengthened legal requirements concerning recycled content in batteries and strategic industrial components.

5.4 Innovation actors: basic science and emerging business models

To map the innovation ecosystem associated with lithium and niobium, patent ownership was analysed through the Applicants field. Applicant names underwent linguistic normalisation and automated classification into functional categories — universities/ICTs, mining firms, METS companies and others — followed by manual curation to correct inconsistencies and consolidate subsidiaries belonging to the same corporate groups.

The ten leading global applicants are presented in Table 1.

Table 1 – Top 10 applicants, actor type and value chain function

Rank	Patent Applicant	Organisational Classification
1°	Univ Central South	UNIVERSITY ICT
2°	Univ Northeastern	UNIVERSITY ICT
3°	Inst Process Eng CAS	UNIVERSITY ICT
4°	Univ Kunming Science Technology	UNIVERSITY ICT
5°	Inst of Multipurpose Utiliz. of Mineral Resources	UNIVERSITY ICT
6°	Lilac Solutions Inc US	OTHER
7°	Beijing Res Inst Chemical Eng Metallurgy	UNIVERSITY ICT
8°	Univ Jiangxi Sci Technology	UNIVERSITY ICT
9°	BGRIMM Tech Group Co Ltd	OTHER
10°	Guangdong Brup Recycling (and affiliates)	OTHER

Source: Authors' own elaboration.

The results indicate a clear predominance of Chinese scientific institutions in this technological domain. Among the leading applicants are major academic and research institutions such as Central South University, Northeastern University, the Institute of Process Engineering of the Chinese Academy of Sciences, Kunming University of Science and Technology, and the Institute of Multipurpose Utilisation of Mineral Resources.

Taken together, these institutions account for a substantial proportion of all patent families identified, significantly exceeding the presence of large global mining corporations. This pattern suggests that the technological challenges associated with critical mineral separation and purification remain strongly dependent on scientific research and experimental development, particularly in chemistry, thermodynamics and process engineering.

Within the private sector, two dominant business models emerge. The first consists of vertically integrated Asian producers, especially firms operating in China and South Korea, combining mining, smelting and downstream refining capabilities across relatively integrated value chains. The second includes a smaller group of highly specialised firms focused on disruptive extraction technologies, particularly Direct Lithium Extraction (DLE).

Finally, the results also highlight the growing relevance of actors linked to circular economy strategies. Firms dedicated to battery recycling and critical metal recovery from industrial residues increasingly appear among major patent holders, including subsidiaries of battery manufacturers and Japanese firms specialised in recovering valuable metals. This movement indicates that a significant portion of recent inventive effort is being redirected from primary ore extraction towards secondary resource recovery, broadening the concept of mineral extraction itself.

5.5 Geographical distribution of innovation: the geopolitics of refining

The geographical distribution of innovation was analysed through the first filing jurisdiction of each patent family, extracted from publication number data. This method allows identification of the jurisdiction in which legal protection was first sought, serving as a proxy for technological origin or primary legal anchoring.

The results are presented in Figure 3.

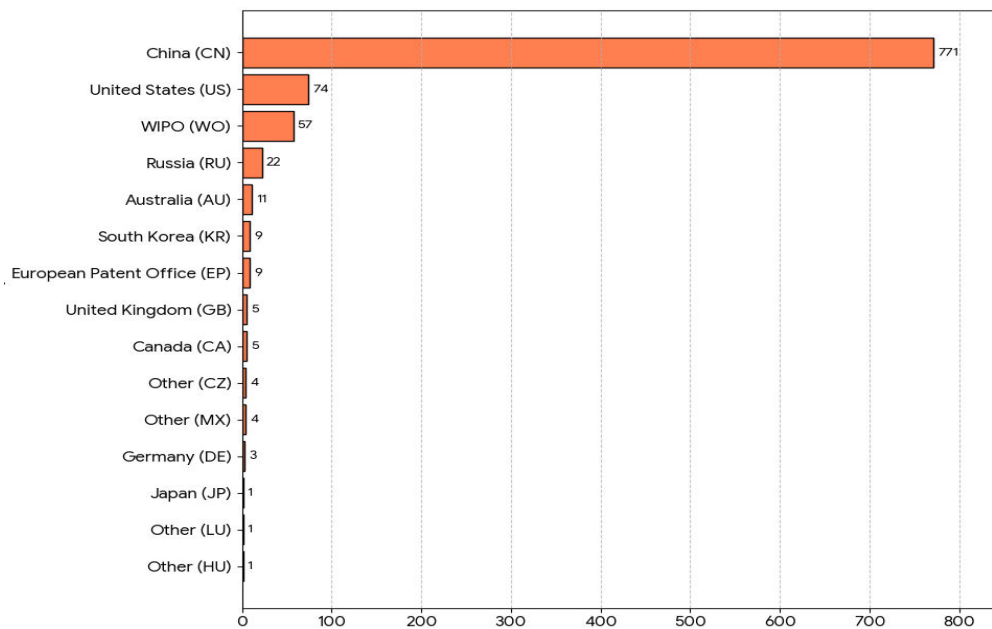


Figure 3 – Frequency of first filing jurisdictions by country

Source: Authors’ own elaboration.

The results reveal a highly concentrated geographical pattern, with important implications for the geopolitics of critical mineral chains. The most striking feature is the predominance of China, whose patent office accounts for the majority of first filings. This indicates that a large proportion of technological knowledge related to lithium and niobium refining is initially protected within China’s intellectual property system.

This finding is fully consistent with the dominance of Chinese research institutions identified in the applicant analysis and suggests a coordinated strategy of technological consolidation across the value chain. By contrast, jurisdictions associated with the Western industrial core appear in secondary positions. The United States ranks second, followed by international filings under the Patent Cooperation Treaty (WO).

The relevance of WO filings suggests that some firms seek broad and flexible legal protection for chemical routes and refining technologies intended for multiple markets. A particularly important finding concerns the disconnect between mineral reserve geography and technological ownership.

Countries with major lithium and niobium reserves (including Australia, Canada, Brazil and Russia) remain comparatively marginal as first filing jurisdictions. This suggests that while these countries occupy central positions in primary extraction and mineral exports, higher-value technological capabilities related to chemical refining, hydrometallurgy and circular economy remain concentrated in technological hubs, particularly in Asia.

This asymmetry reinforces the strategic importance of policies aimed at technological capability-building and effective technology transfer, in order to avoid reproducing an international division of labour in which innovation and value capture remain detached from mineral-producing regions.

VI. FINAL CONSIDERATIONS

The results demonstrate that patent-based technological prospecting can operate as a robust analytical instrument for the mineral sector when supported by a carefully designed methodological strategy. The initial exploratory query confirmed that searches based exclusively on unrestricted vocabulary generate a high volume of false positives, mainly due to the lexical ambiguity associated with terms such as mining and the widespread presence of lithium in technological applications unrelated to mineral extraction. Only the adoption of a hybrid search strategy, combining sector-specific keywords, mining and extractive metallurgy CPC codes, and exclusion operators, made it possible to isolate a final corpus of 980 patent families effectively associated with lithium and niobium extraction, beneficiation and refining processes.

The resulting patent landscape indicates that the current technological frontier is concentrated less on physical extraction itself and increasingly on chemical and thermochemical routes for mineral separation, purification and upgrading of low-grade ores. This finding reinforces the understanding that, in critical mineral value chains, technological competitiveness depends increasingly on downstream process sophistication rather than solely on geological availability.

The analysis of applicants and geographical distribution revealed a marked asymmetry in technological ownership. Organisational leadership is concentrated not in large mining corporations or traditional Mining Equipment, Technology and Services (METS) firms, but mainly in universities and research institutes, with strong predominance of Chinese institutions responsible for most patent families identified. In geographical terms, most inventions have the China National Intellectual Property Administration as first filing jurisdiction, while countries with significant reserves, such as Brazil, Australia and Canada, show comparatively limited participation as primary origins of intellectual property.

This mismatch between reserve location and technological ownership suggests an international division of labour in which technological value capture is concentrated in research-intensive centres rather than in mineral-producing territories. For mineral-rich countries, this reinforces the strategic importance of technological intelligence mechanisms capable of identifying dominant technological actors and emerging innovation routes.

Based on these findings, three relevant pathways for technology transfer emerge. First, the distance between organisations generating core process knowledge and those directly involved in mineral production indicates opportunities for licensing agreements, technical cooperation and joint development aimed at incorporating hydrometallurgical and pyrometallurgical routes into Brazilian industrial operations. Second, the strong presence of the CPC meta-classification Y02P10/20 indicates opportunities in environmentally oriented technologies related to cleaner processing, waste reduction and circular economy solutions, particularly relevant for firms seeking alignment with ESG commitments. Third, the presence of specialised firms operating in niches such as Direct Lithium Extraction suggests that strategic partnerships or targeted investments may provide access to disruptive process technologies.

It is therefore concluded that patent-based technological prospecting constitutes a viable and strategically relevant instrument for supporting innovation and technology transfer decisions in critical minerals. More than geological reserves alone, competitiveness in the energy transition will increasingly depend on the ability to identify, select and internalise advanced processing technologies characterised by greater efficiency, lower environmental impact and higher knowledge intensity.

For future research, it is recommended that patent families be cross-analysed with scientific publications and collaboration networks in order to better understand the effective pathways of technology transfer from research environments to industrial application in the Brazilian context.

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