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Review article

How important is the scientific knowledge gap between leading research and producing countries of lithium?

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ABSTRACT

Abstract: The strong increase in global demand for lithium, driven by the ion battery market and the use of this non-metallic mineral in various economic sectors such as mining (as a non-metallic and non-renewable mineral), health, technology, and geopolitical issues, has fueled the development of disruptive innovation, with new products linked to knowledge creation. These developments have included, among other things, the use of new processing techniques, the creation of new high-capacity cathode materials, the investigation of new sources of lithium, and increased recycling of lithium-ion batteries. This article's primary goal is to assess how this knowledge gap is related with innovation issues using the analysis of the scholar as a case study. Additionally, the examination of public policy related to the lithium business will be continued and updated in this publication. This study uses computerized bibliometric analysis based on the R program and Biblioshiny, a web interface for Bibliometrix analysis. One of the earliest studies to examine the discrepancy between lithium production and consumption based on innovation is this one. The research's contribution is to highlight the disparities and gaps in knowledge generation between producer and consumer countries, which creates a great opportunity to develop better public policies that use existing knowledge and promote collaborations between mining and technology companies for the development of a more sustainable, efficient, effective and competitive industry with future societies.

1. Introduction

There is some controversy about the conditions for lithium to be classified as a disruptive innovation, since it has been known and used since the beginning of the 18th century in various applications. However, in recent decades, it has gained prominence due to the increasing demand for the mineral, driven primarily by the rapid growth of the lithium-ion battery industry, and its potential to change the way electric devices can be used from stationary to portable [1]. This has revolutionized the telecommunications industry, and as energy storage capacity and lifespan have improved, it has transformed the household appliance industry, the tools industry and most recently, the automotive industry.

These innovations have included the adoption of new processing technologies, the development of high-capacity cathode materials, the exploration of new sources of lithium and the increased recycling of lithium-ion batteries, among other topics. Additionally, the

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growing demand for lithium and the transition to electric vehicles and renewable energy have led to the creation of new business models around lithium and battery production and distribution, such as the development of battery "megafactories" and the implementation of long-term supply agreements.

Everyone agrees that the extraction and creation of added value from lithium will play a significant role in the technological advancement of the entire planet. Among many other uses, lithium is a crucial component of the lithium-ion batteries used in electric vehicles. The demand for electric vehicles, which has risen sharply in recent years due to the Tesla revolution [2], is anticipated to surpass 30 % of annual vehicle sales by 2030 [3]. Lithium is a crucial component of the technology that powers mobile phones, laptops, power tools, and energy storage devices in general in addition to electric cars. Just forgetting its expanding role in the medical management of bipolar disorder and other mental disorders including Alzheimer's disease and dementia [4,5].

In this sense, it could be considered that the growing demand for lithium and the innovations associated with its extraction, processing, and use in lithium-ion batteries have been disruptive in the energy industry, electronic consumer goods and transportation, leading to a significant transformation in global energy and transportation markets.

This, in turn, has driven significant innovations in the way lithium is extracted, processed and used, and has incentivized basic and applied scientific research around this mineral. This productive dynamic is accompanied by a constant development of scientific knowledge in the field, which grows day by day, attracting global geopolitical actors who promote scientific development. On the other hand, emerging players with available resources are also positioning themselves in this field and need to innovate in terms of extraction and processing to add value to the natural resources they possess.

On the other hand, this increase in demand has fueled competition among countries that have the capacity to add value, driving applied development and research in the field of lithium, as well as those countries that possess the main reserves and seek to consolidate their strategic position as leading suppliers and develop their industries to add value locally. It also applies to other countries that aim to establish the foundations for participating in the global market and subsequently develop their industrialization and add value locally. In all these cases, the ability to generate scientific knowledge around the mineral has become a strategic action in the medium and long term for all countries, both leaders in industrialization and those that possess the mineral.

Concerns have been raised concerning the innovation that lithium and its products offer [6]. The lithium mining, processing, and use processes have undergone significant advancements as a result of the rising demand for lithium during the past ten years, which is mostly attributable to the lithium-ion battery industry's explosive expansion. These developments have included, among other things, the use of new processing techniques, the creation of new high-capacity cathode materials, the investigation of new sources of lithium, and increased recycling of lithium-ion batteries.

Additionally, new business models for the production and distribution of lithium and batteries have been developed as a result of the rising demand for lithium and the shift toward electric vehicles and renewable energy sources. Examples include the development of battery "gigafactories" and the implementation of long-term supply agreements [7] and potential of lithium recycling in a context of circular economy [8].

In this regard, it could be argued that the rising demand for lithium and the technological advancements related to its extraction, processing, and use in lithium-ion batteries have had a disruptive effect on the energy, consumer electronics and transportation sectors

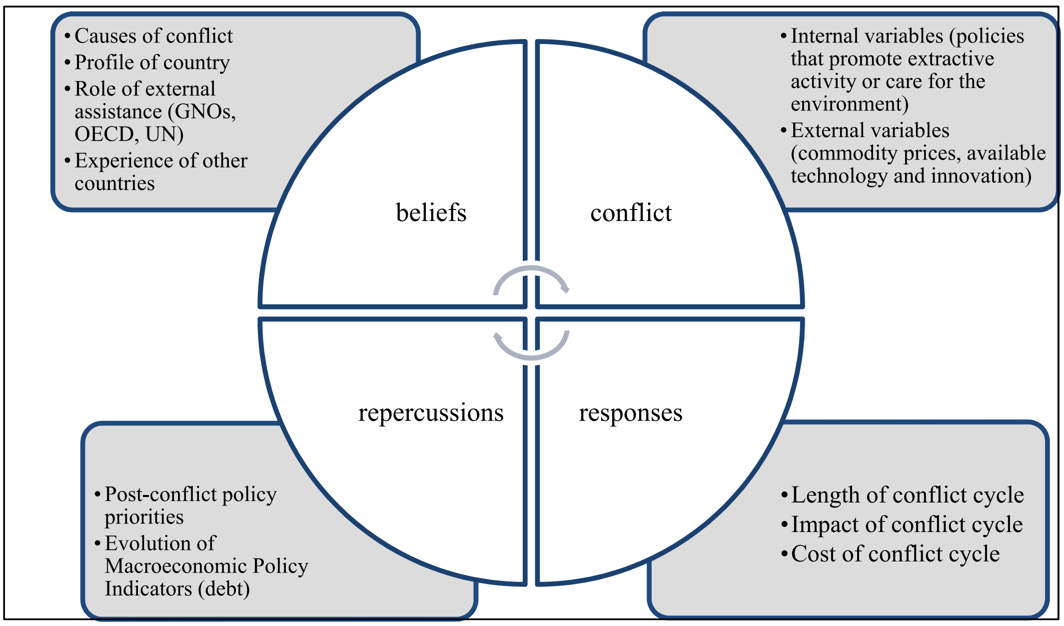


Fig. 1. Conflict cycle.
Source: Own elaboration.

[9,10]. As a result, the energy and transportation markets around the world have undergone a significant transformation.

Nicholson [11] in the 1970s shows that the use of lithium carbonate in aluminum production became a very important commercial-scale end use as early as the 1950s. Then in the 1990s it had a significant increase due to its medical uses and since 2010 it has had an explosive increase due to its electronic uses. This productive dynamic is accompanied by a steadily expanding body of scientific knowledge in the field, where global geopolitical actors are positioned to support scientific advancement and, on the other hand, emerging actors with the resources who must innovate around resource extraction and processing in order to try to increase the value of the natural resources they possess (appendix 1).

It is crucial to point out that the lithium sector has negative externalities on the environment and communities, which leads to disputes with socioeconomic and geopolitical elements in countries like Argentina, Bolivia, and Chile, which make up the so-called lithium triangle in Latin America [12]. The conflict cycle, distribution and players are described by the ecological distribution of resources, pollution produced on sacrifice zones, and financial and power inequities that result from this industrial metabolism [13]. Authors analyses, the beliefs, conflict, responses, and repercussions, are organized in Fig. 1. ([14]; [15]; [16]).

Some studies have looked at the geopolitical scope of the post-Covid era, which should surely be included in future Lithium public policy [17]. This is especially important when considering the divergences in geopolitical interests associated to lithium in South America, which can set off a conflict cycle like the one depicted in Fig. 1 [18].

This study aims to balance both initiatives by examining the factors influencing the expansion of this field of study's scope and concentration. Authors evaluate the state of research on the concerns of lithium ore extraction and utilization based on a bibliometric review.

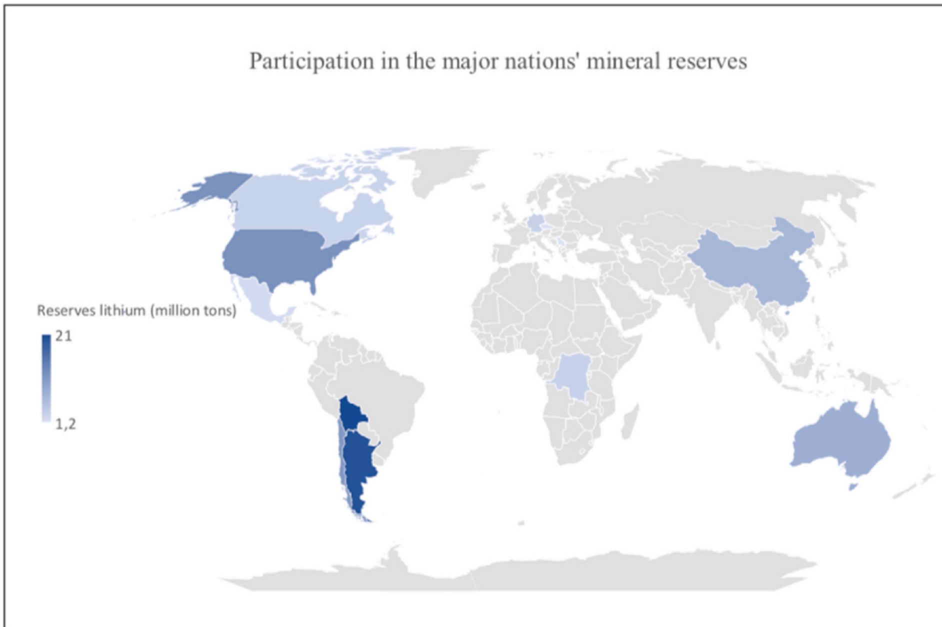
This article also seeks to examine the evolution of scientific production around lithium from 1970 through 2022. This work is significant since it is the first to use Biblioshiny, an online interface for bibliometrix analysis built on the R software (Gagolewski, 2011; Moral Muoz et al., 2020; Saikia, 2020), to explore the Lithium literary paths.

The essay is organized as follows: Section 2 describes a bibliometric study of relevant articles that have undergone peer review. The Lithium issue has been taken into consideration from many scientific domains, according to Section 3's identification of central organizations, countries, and scientific collaborations. In its final paragraph, Section 4 suggests some restrictions and a course for future research.

2. Background

2.1. Leaders in lithium supply and demand internationally

The international landscape of lithium supply and demand is primarily shaped by several key players that contribute significantly to the global lithium market. Australia stands as a dominant force in lithium supply, owing to its vast lithium reserves and well-established mining operations [19]. The country's advanced extraction and processing techniques have positioned it as the leading global producer of lithium. Chile, renowned for its extensive lithium reserves concentrated in the Salar de Atacama, is another major



id	Producers	Reserves lithium 2022 (million tons))
1	Bolivia	21,00
2	Argentina	20,00
3	United States	12,00
4	Chile	11,00
5	Australia	7,90
6	China	6,80
7	Germany	3,20
8	Canada	2,90
9	Congo	3,00
10	Mexico	1,70
11	Czech Republic	1,30
12	Serbia	1,20
13	Russia	1,00
14	Peru	0,88
15	Mali	0,84
16	Brazil	0,73
17	Zimbabwe	0,69
18	Spain	0,32
19	Portugal	0,27
20	Namibia	0,23
21	Ghana	0,18
22	Finland	0,07
23	Austria	0,06
24	Kazajistan	0,05

Fig. 2. Countries with the largest lithium reserves in the world (2022).
Source: Own elaboration based on information from USGS, Mineral Commodity Summaries Geological Survey (2022)

player in the lithium supply chain [20]. Leveraging advanced mining practices, Chile has emerged as a prominent lithium producer, making substantial contributions to the global supply. Additionally, China plays a pivotal role as both a producer and consumer of lithium [21]. With its thriving lithium mining sector, proficient extraction capabilities, and rapidly expanding electric vehicle industry, China commands a significant share of global lithium supply and drives substantial demand.

On the demand side, China continues to dominate the international lithium market due to its robust electric vehicle industry and ambitious renewable energy goals [22,23]. As the largest consumer of lithium globally, China's demand for lithium-ion batteries continues to surge, further influencing the global lithium demand. The United States is another notable leader in lithium demand, driven by the growing electric vehicle market and the increased adoption of renewable energy storage systems [24]. Within Europe, the European Union, led by countries such as Germany and France, exhibits a rising demand for lithium, fueled by stringent emission standards and the promotion of electric vehicles [25]. South Korea and Japan, renowned for their well-developed electric vehicle industries, contribute significantly to the global lithium demand, while India emerges as a potential future leader due to its ambitious plans for electric vehicle adoption and renewable energy storage [26]. Collectively, these leaders in lithium demand reflect the global transition towards sustainable transportation and clean energy, propelling the lithium market to new heights.

The countries with the largest lithium reserves in the world, as per the provided statistical information and the previous discussion, are Bolivia, Argentina, United States of America, Chile and Australia, which stand out as the frontrunners in global lithium reserves [27] in Fig. 2.

Bolivia leads with an impressive 21.00 million tons, while Argentina closely follows with 20.00 million tons [28,29]. These countries possess vast lithium resources concentrated in their rich salt flats, such as Bolivia's Salar de Uyuni and Argentina's Salar del Hombre Muerto [24]. The significant lithium reserves in these nations solidify their pivotal roles as major suppliers, enabling them to actively participate in the production and export of lithium to meet the surging global demand.

The United States of America and Chile also hold substantial lithium reserves, with 12.00 million tons and 11.00 million tons. These countries boast advanced mining operations and extraction technologies, positioning them as significant players in the global lithium supply chain. Australia, with 7.90 million tons of lithium reserves, has emerged as a key contributor to global supply, capitalizing on its efficient extraction and processing capabilities. China, with 6.80 million tons, leverages its robust lithium mining sector and burgeoning electric vehicle industry to influence both supply and demand in the global lithium market [30].

While Bolivia and Argentina dominate in terms of lithium reserves, it is important to recognize the contributions of other countries as well [31]. Germany, Canada, and Congo, each with substantial reserves, bolster the global lithium supply and play vital roles in meeting the growing demand. These diverse lithium reserves across multiple countries enhance the stability and resilience of the global lithium market, ensuring a reliable supply chain for industries dependent on lithium-ion batteries and energy storage systems. As the world transitions towards cleaner and more sustainable energy sources, the strategic significance of these countries' lithium reserves cannot be overstated, as they pave the way for the development of advanced technologies and the electrification of transportation on a global scale.

2.2. Innovation and generation of knowledge around lithium

As demonstrated by Schumpeter & Nichol [32], innovation modifies the forms of production in their processes in firms, and it is a notion frequently employed by numerous economic activities. There are various sorts of innovation [33] including process, product, organizational, and marketing. However, the Oslo manual includes business goods and processes [34]).

The literature has multiple kinds of innovation. Within these, we can discover radical, incremental, technological and non-technological innovation, as well as disruptive innovation [35–40].

Countries with larger revenues can invest more in their technology and information technologies, which is reflected in the outcomes of their innovation.

As illustrated by Fig. 2, innovation is a major issue because it can either start or resolve a conflict over the extraction and use of a material resource. According to the Global Innovation Index Database proposed by WIPO (World Intellectual Property Organization) for the year 2022, Switzerland ranks first with a score of 64.6, followed by the United States (61.8), Sweden (61.6), the United Kingdom (59.7), the Netherlands (58.0), the Republic of Korea (57.8), Singapore (57.3), Germany (57.2), Finland (56.9), and Denmark (55.9) [41].

It is important to note that no Latin American country appears in this ranking, according to WIPO data. Only the United States and Germany repeat the information on mineral deposits that has already been provided in the previous section.

Merigó et al. [42] conducted bibliometrics research on innovation between 1889 and 2013. According to this author, the major countries that stand out are the United States and the United Kingdom.

Innovation and the generation of knowledge around lithium have become paramount as the demand for this critical resource continues to rise. With lithium serving as a key component in energy storage, electric vehicles, and renewable technologies, countries, research institutions, and industry players are actively engaged in advancing knowledge and pushing the boundaries of lithium-related technologies [43]. This pursuit of innovation encompasses various aspects, including lithium extraction and processing techniques, battery technologies, and sustainable production practices.

In the realm of lithium extraction and processing, innovative methods are being explored to improve efficiency and reduce environmental impact. Researchers are investigating novel extraction techniques, such as selective lithium-ion exchange membranes and advanced separation technologies, to enhance the yield and purity of lithium extraction from brines and ores (G. [44]). Furthermore, advancements in lithium-ion battery technologies, such as the exploration of new cathode and anode materials, solid-state batteries, and next-generation lithium-ion designs, are fueling breakthroughs in energy storage capabilities, including longer lifespans, higher energy density, and faster charging rates [45].

The generation of knowledge around lithium is not limited to technological advancements alone [46]. It also encompasses sustainable practices and the development of comprehensive lifecycle assessments [47]. Efforts are being made to better understand the environmental and social impacts associated with lithium extraction, processing, and recycling [48]. This knowledge is crucial in formulating responsible mining practices, minimizing ecological footprint, and ensuring the ethical sourcing of lithium [49]. Additionally, research institutions and industry collaborations are focusing on understanding the economic, policy, and market dynamics surrounding lithium to facilitate informed decision-making and foster the development of a sustainable lithium value chain [50,51].

Overall, innovation and the generation of knowledge around lithium are crucial for unlocking the full potential of this valuable resource. Continued research and collaboration will pave the way for advancements in lithium-related technologies, sustainability practices, and the responsible utilization of lithium reserves contributing to the development of local communities (W. [52]). By fostering innovation and knowledge exchange, we can ensure the efficient and sustainable use of lithium, contributing to the transition towards a cleaner and more electrified future.

3. Materials and methods

This section describes the data sources and the research method used to identify and analyze the study.

3.1. Data sources and collection

This study gathers data from the Web of Science (WoS) Core Collection in order to construct the bibliometric analysis regarding knowledge gaps on numerous research subjects around Lithium. This database has been chosen because of its consistency and track record of collecting records and because it has similar quality characteristics to other databases such as Scopus [53].

This article selects the WoS (Web of Sciences) collection as the data source (https://www.webofscience.com/wos/woscc/basic-search). WoS is an online scientific information service, provided by Clarivate Analytics (formerly Thomson Reuters), integrated with ISI Web of Knowledge, WoK, ideas across disciplines and time from almost 1.9 billion cited references from over 171 million records (WoS 2021).

It provides access to a set of databases containing citations to scientific journal articles, books and other printed material covering all fields of academic knowledge. Web of Science, is the collection of databases of bibliographic references and citations of periodicals that collect information from 1900 to the present. The WoS database includes more than 15,000 journals and 50,000,000 papers classified in 251 subject categories and 151 subject areas [54].

The WoS is composed of the Core Collection, which includes the indexes of Sciences, Social Sciences and Arts and Humanities, as well as the Proceedings of both Sciences and Social Sciences and Humanities, together with the tools for analysis and evaluation, such as the Journal Citation Report and Essential Science Indicators. In addition, it has the databases that complement it included in the license for Spain: Medline, Scielo and Korean Citation Index.

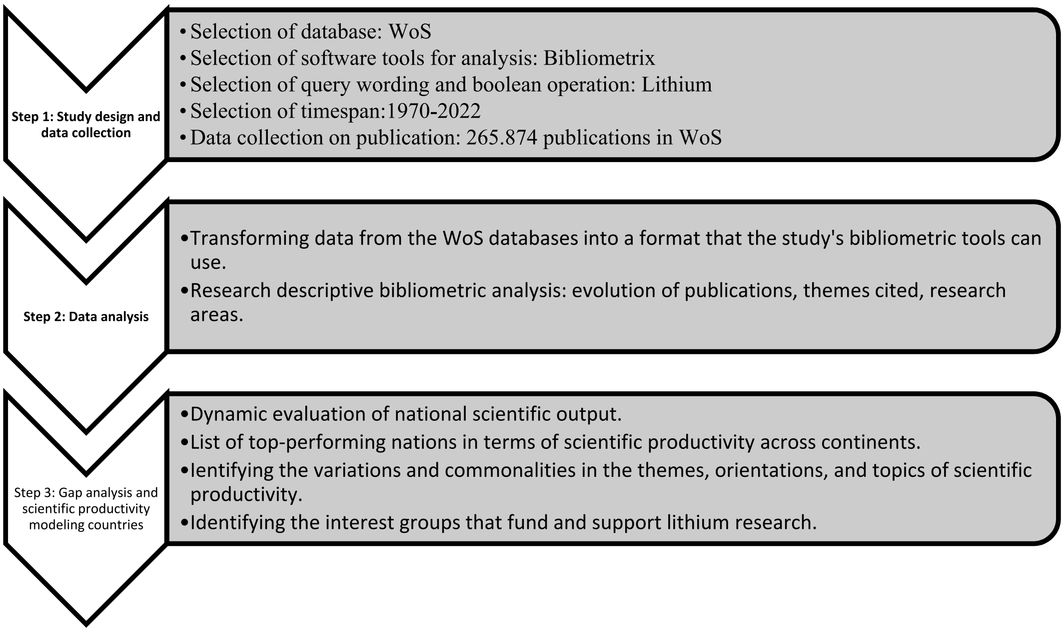


Fig. 3. Research methodology.
Source: Own elaboration.

The study considers the 52-year period from 1970 to 2022. Our search shows 265.874 research papers on this subject throughout this time (retrieved on May 2, 2023). The entered search terms are [Lithium], the search language is all languages. The WoS bibliographic citation database includes various types of documents, but only original articles and Review articles were considered in the present analysis. The complete records for each publication retrieved during the search were converted as a text plain generic file and imported into Bibliometrix and Biblioshiny package R Gnu [55].

3.2. Research method and data

3.2.1. Research software

Bibliometrix and Biblioshiny open source packages 3.1 version are used from the R language environment. Bibliometrix allows completing the whole process of scientific literature analysis and data processing. Biblioshiny collects the basic Bibliometrix code and builds an online data analysis framework and enables users to perform important bibliometric and visual analysis based on an interactive web interface [56].

3.2.2. Analysis strategy

To create two groups that will be contrasted, the productivity of the nations related to the lithium issue was examined. The first takes into account the top 4 international producers of scholarly articles that explain more than 50 % of the scientific productivity around lithium. The second group takes into account the 21 non-members of the first elite group that account for the majority of the world's mineral reserves.

Then, a number of bibliometric analyses were performed, taking into account productivity dynamics through time and modeling growth, to identify discrepancies between the scientific production of the two groups. In order to identify the areas of interest as well as the broad research fields that the publications were destined for, the themes citation where the publications were concentrated were then summarized. To identify the organizations that promote and finance research on lithium in both categories, the affiliations of the primary author and the organizations that funded papers have also been examined (Fig. 3).

The thematic areas to which the scientific papers indexed in the WoS database belong are represented by the "citation topics" (also known as "citation categories"). Using these categories, papers are categorized and arranged according to their subject matter and academic discipline.

The topics cited in WoS are determined by examining the citations that scientific articles have received. Documents that cite other documents offer details about the cited document's subject. In order to make it simple to locate and evaluate relevant documents in a given field, WOS employs this data to categorize citations to papers.

There are numerous academic topics and academic disciplines represented in the WoS citation categories, including the natural sciences, social sciences, engineering, medicine, life sciences, computer sciences, and environmental sciences, among others. The sciences of physics, chemistry, biology, economics, psychology, the environment, health sciences, and the study of energy are a few examples of citation categories in WoS.

These citation categories enable scholars to focus on a single topic of interest while more thoroughly and precisely exploring and analyzing the scientific literature. They can also be used to track an article's effect and importance over time and to spot research patterns in other sectors. It is crucial to remember that the citation categories in WoS are subject to recurring upgrades and adjustments to reflect advancements and innovative fields of scientific study.

Table 1
Top 20 producers of lithium-related scientific articles (1970–2022).

Ranking	Country	Papers	Paper %	Acum paper %
1	China	87.353	26,0 %	26,0 %
2	USA	52.257	15,6 %	41,6 %
3	Japan	21.119	6,3 %	47,9 %
4	Germany	19.843	5,9 %	53,8 %
5	South Korea	15.231	4,5 %	58,3 %
6	France	12.517	3,7 %	62,1 %
7	England	11.353	3,4 %	65,4 %
8	India	10.833	3,2 %	68,7 %
9	Russia	8.200	2,4 %	71,1 %
10	Canada	8.080	2,4 %	73,5 %
11	Italy	7.638	2,3 %	75,8 %
12	Australia	7.049	2,1 %	77,9 %
13	Spain	7.039	2,1 %	80,0 %
14	Taiwan	4.106	1,2 %	81,2 %
15	Sweden	3.401	1,0 %	82,2 %
16	Singapore	3.375	1,0 %	83,2 %
17	Poland	3.351	1,0 %	84,2 %
18	Brazil	3.184	0,9 %	85,2 %
19	Switzerland	3.163	0,9 %	86,1 %
20	Netherlands	2.275	0,7 %	86,8 %

Source: Own elaboration with data of WoS database.

Scientific publications are organized and classified using "research areas" in the WoS database. Scholarly publications are categorized into these research topics because they represent large and diverse fields of study.

The research areas in WoS cover a variety of disciplines and sub-disciplines and give an overview of the broader subjects. In order to make it simpler to search for and study the scientific literature in a particular area of interest, these categories are used to classify and name the articles.

These research topics offer a comprehensive organizing framework for looking for and evaluating scientific papers according to their general subject. The study areas in WoS cover a wide range of disciplines (for example, physical and mathematical sciences, life sciences, health sciences, etc.) and subfields within each subject area, but they are not as narrowly focused as citation categories or keywords.

To filter and focus the search results and locate more precise publications in a particular area of interest, research areas can be used in conjunction with other search criteria, such as citation categories.

4. Results and discussion

In this section, we'll examine the findings of a search for academic works that are discussed. In Table 1, a summary of the top 20 countries can be seen regarding scientific production related to lithium across various fields and topics.

4.1. Leaders in the generation of knowledge around lithium at an international level

In this instance, it is evident that the first four nations account for almost 53 % of all scientific research on lithium between 1970 and 2022. It is also clear that China and the United States, which together accounted for 41 % of all papers published during the time, are at the forefront of scientific creation.

Fig. 4 depicts the growth patterns of the main nations' scientific publications, which account for little over 53 % of the global production as recorded by WoS (China, USA, Japan and Germany). In this instance, it is clear that the countries exhibit growth that is sustained over time and exhibit growth rates that are similar to exponential functions. These growth rates are shown in the figure as straight lines on a semi-logarithmic graph.

The temporal lineal regression for each of the nations with an exponential growth curve is also shown in Fig. 4, and the coefficient that goes along with the exponent can be taken to represent the nation's annual growth rate. In this instance, it is clear that China, with an average annual growth rate of 20.5 %, is the nation with the highest rate of scientific production, followed by Japan with a rate of 9.3 %, the USA with a rate of 7.8 %, and Germany below with a rate of 6.2 %. The regressions reveal significant disparities between the top-performing nations in terms of their potential to produce new scientific knowledge, with China taking the lead in this area.

It can be noted that different nations have varying times when they reach regular scientific productivity with sustained growth rates, such as China, which has done so since the early 1990s. In the case of the United States, it has been sustained since the year 2000. Germany and Japan, on the other hand, have consistently increased their scientific productivity since the early 1990s, but they have not been able to do so at rates that have remained stable over time.

4.2. Creation of a knowledge base for the nations that produce the mineral resource

Now we consider the creation of knowledge of the nations that have the largest reserves around the mineral, and that some of them currently have a relevant participation in the global production around lithium. Table 2 lists the nations with the largest lithium reserves worldwide, their market shares, and how they participated in the creation of scientific knowledge on lithium.

Table 2 shows that only 11 of the 24 nations with the biggest mineral reserves now contribute considerably to its production, with three of those nations—Australia, Chile, and China—concentrating world output. It is clear from looking at their scientific output that

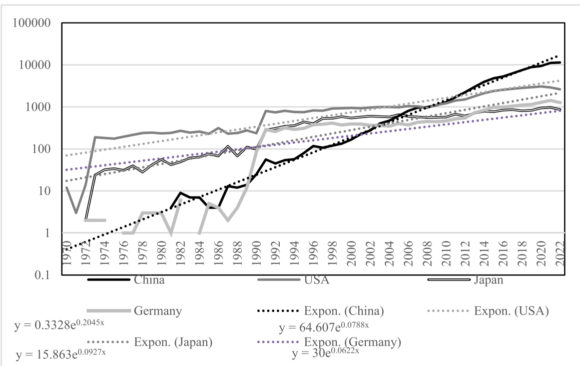


Fig. 4. Dynamic shift in the top 4 nations' scientific output from 1970 to 2022.
Source: Own elaboration with data of WoS database.

Table 2
Participation in the major nations' mineral reserves, production and scientific research, and reserve holdings in summary.

id	Producers	Reserves lithium 2022 (million tons))	Percentage share of reserves (%)	Production lithium 2021 (metric tons)	Percentage share of production (%)	Percentage share papers Lithium items (%)
1	Bolivia	21,00	21,6 %	102	0,1 %	0,01
2	Argentina	20,00	20,6 %	9.989	8,7 %	0,23
3	United States	12,00	12,3 %	5.000	4,3 %	15,60
4	Chile	11,00	11,3 %	30.665	26,6 %	0,24
5	Australia	7,90	8,1 %	55.281	48,0 %	2,10
6	China	6,80	7,0 %	14.000	12,1 %	26,00
7	Germany	3,20	3,3 %			5,90
8	Canada	2,90	3,0 %	4.092	3,6 %	2,40
9	Congo	3,00	3,1 %			0,00
10	Mexico	1,70	1,7 %			0,40
11	Czech Republic	1,30	1,3 %			0,40
12	Serbia	1,20	1,2 %			0,07
13	Russia	1,00	1,0 %			2,40
14	Peru	0,88	0,9 %			0,01
15	Mali	0,84	0,9 %			0,00
16	Brazil	0,73	0,8 %	255	0,2 %	0,95
17	Zimbabwe	0,69	0,7 %	476	0,4 %	0,01
18	Spain	0,32	0,3 %			2,10
19	Portugal	0,27	0,3 %	129	0,1 %	0,34
20	Namibia	0,23	0,2 %	88	0,1 %	0,00
21	Ghana	0,18	0,2 %			0,01
22	Finland	0,07	0,1 %			0,27
23	Austria	0,06	0,1 %			0,47
24	Kazajistan	0,05	0,1 %			0,11

Source. Own elaboration based on data from Mineral Commodity Summaries 2023, U.S. Geological Survey (https://pubs.er.usgs.gov/publication/mcs2023), WOS.

only 7 of them contribute significantly to the overall scientific output. In comparison to other nations, China and the USA stand out in terms of engagement in scientific creation.

Then, China, the United States, Australia, and Canada can be named as the nations with the largest lithium reserves, an important portion in the mineral's production, and relevant scientific output. As a result, these nations hold a dominant position in the lithium industry and contribute significantly to its development, production, and research. This suggests that these nations possess a tactical edge in terms of lithium-related natural resources and specialized knowledge. Additionally, given that lithium is a crucial component in the production of lithium-ion batteries, this finding implies that these nations can have a big impact on associated industries like rechargeable batteries and electric mobility.

It is also possible to identify nations like Germany, Russia, and Spain that, despite not contributing significantly to mineral production, have mineral reserves and relevant scientific output. It may be said that these nations have a significant advantage when it comes to natural resources, especially in regard to lithium. Large lithium deposits suggest great potential for this mineral's development and production. Additionally, the pertinent scientific output surrounding lithium demonstrates a desire and ability to investigate and create applications and technology related to lithium. In the medium term, these nations may be pushing innovation in a variety of sectors and fields, which could result in technological advances and a dominant position in the energy and electric mobility industries.

It is particularly important to bear in mind that relevant scientific output alone does not ensure that lithium-related goods may be successfully manufactured and sold. The development and utilization of lithium reserves are also influenced by other factors, such as investment in infrastructure, political stability, governmental regulations, and industrial capacities.

It is also probable to identify a collection of nations, including Bolivia, Argentina, Chile, and to some degree, Brazil, Zimbabwe, Spain, Portugal, and Namibia, that possess the majority of mineral resources and relevant output. The finding that follows is that these nations hold a significant position in terms of natural resources, enabling them to play a significant role in the production and supply of lithium on the global market.

To take full advantage of the potential of lithium, these nations may be highly reliant on outside technology and knowledge, as seen by their minimal participation in scientific creation. They might be less interested in funding the development of related technologies and more concerned with extracting and exporting the ore.

This suggests that these nations might be more exposed over the long term in terms of innovation and competitiveness in the lithium business. Depending too heavily on outside information can hinder your capacity to advance technology and preserve a competitive edge in a constantly shifting industry.

Therefore, these nations could take into account the significance of increasing their scientific and technological capabilities in relation to lithium, through the encouragement of regional research and development, international cooperation, and investments in the field's infrastructure and human resources. Insofar as they can invest some of the proceeds from its sale in proactive development and innovation policies in the various sectors of the mineral production and value-adding chain, this would enable them to diversify their economy and ensure a more comprehensive and sustainable role in the lithium industry over time.

The rest of the countries, such as Kazakhstan, the Congo, Mexico, the Czech Republic, Serbia, Peru, Mali, Ghana, Finland and Austria, have mineral deposits but do not engage in mineral production. Untapped potential in these nations suggests great potential in terms of natural resources. However, their lack of participation in the ore's production and scientific research indicate that this potential is not being fully realized or developed; it likely requires investment in lithium-related infrastructure, technologies, and capabilities, and they can profit from foreign investment and development of the lithium industry, which would enable them to generate jobs, strengthen their economies, and make better use of their natural resources.

On the opposite hand, since these nations have lithium reserves, chances for cooperation present themselves. They may want to consider working with nations that have a history of producing lithium and conducting research related to it. In order to advance their own lithium industry and lessen their reliance on outside sources, they would be able to gain access to technical and technological knowledge, form strategic alliances, and benefit from others' experience. This is because a lack of mineral production and pertinent scientific production could also point to a significant reliance on the importation of lithium-related goods and technologies. As these nations may be impacted by the shifts and fluctuation in the global market that this mineral may encounter, this could have effects on the long-term energy and economic security of those nations. In conclusion, there is untapped potential in nations that have lithium reserves but do not participate in the mineral's production or pertinent scientific research. They can think about the need for investment, capacity building, global collaboration, and economic diversification in order to benefit from it.

Fig. 5 shows the dynamics of scientific production of the groups mentioned above, leading nations (China, USA, Japan, and Germany) which account for 53.8 % of global aggregate productivity and the nations with the main reserves that do not lead the scientific production around lithium (Bolivia, Argentina, Chile, Australia, Canada, Congo, Mexico, Czech Republic, Serbia, Russia, Peru, Mali, Brazil, Zimbabwe, Spain, Portugal, Namibia, Ghana, Finland, Austria, and Kazakhstan).

The semi-logarithmic graph shows that, like the group of nations with the largest mineral reserves, the top-producing nations in science have a consistent pace of growth in their publications. However, it is clear that the former have a rate (9.88 %) than the 11.14 % provided by the nations with the largest reserves. Take into account that this group is influenced by the scientific output of Russia, Canada, Australia, and lower annual growth Spain, which account for 9 % of all scientific output centered on the lithium-rich regions of the world.

Additionally, it can be established that both groups display scientific productivity in the 1990s that is above the exponential growth tendency, indicating that this was a time of significant invention and advancement. Since 2010, this situation has changed, and scientific production is now approaching an exponential trend—that is, with constant growth rates in its scientific production in the case of leading countries, and a decrease in the rate of scientific production begins.

4.3. Knowledge gaps

For each of the groups of countries examined, the themes cited, and research fields have been examined to take into account any potential knowledge gaps and determine whether there are any variances or similarities in the areas of interest in the scientific publications. The top 20 themes cited by the top producing nations in science and the nations with the largest reserves are included in the following table (see Table 3).

Table 3 shows the variations in the intensity of the topics studied, with Lithium-ion Batteries occupying a prominent position with a

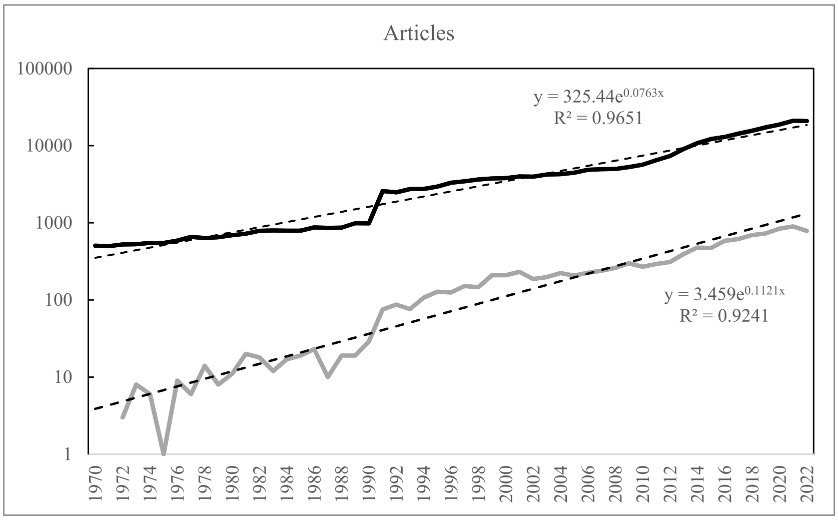


Fig. 5. Scientific output from the top four nations and the nations with the largest lithium reserves.
Source: Own elaboration based on WOS data.

concentration of 23.2 %, followed by Supercapacitor and Lithium-sulfur Batteries with a concentration of 55.1 % of the scientific production of the top producing nations. In contrast, it can be seen that the level of intensity in these themes is different in the group of nations that have sizable reserves of the material, with gap of −9.1 % Lithium-ion Batteries, −7.9 % Lithium-sulfur Batteries, and −7.4 % Supercapacitors. We can infer from the results shown in Table 3 that the top producing nations in science are concentrating on research into lithium-ion batteries, supercapacitors, and lithium-sulfur batteries. This demonstrates that they are making significant progress in these energy storage technologies.

On a broad scale, research efforts are focused on lithium-ion batteries, which stand out as a vital research area in both categories of countries and account for a significant share of both countries with significant material reserves and those with the highest levels of scientific production. Because lithium-ion batteries are utilized in so many different applications, including electric vehicles and electronic devices, there may be a general interest in enhancing and optimizing them.

Countries with significant lithium reserves show less intensity in the topics of interest than countries that are leaders in scientific production, which may be due to different approaches in lithium-related research. The differences in research intensity between the two groups of countries also suggest that countries with lithium reserves may be focusing on other research areas related to this resource, such as lithium extraction and processing, or other uses.

When examining data gathered from lithium producers and consumers, we can identify gaps that, as shown in Fig. 1, can be a source of conflict through numerous strategic concerns connected to countries' innovative capacity and public policies that foster it.

The primary research areas where the leading nations in scientific production and the nations with the most lithium reserves are concentrating their efforts are outlined in the following table (see Table 4).

The first five fields are shown in Table 4, Chemistry (25.4 %), Materials Science (21.6 %), Physics (10.7 %), Electrochemistry (8.8 %), and Energy Fuels (8.0 %), which together account for 51.5 % of the efforts made by the top-producing nations in the field of science. On the other hand, 68.5 % of the scientific production is concentrated in these regions in the major reserve countries. Specifically: Electrochemistry 6.9 %, Energy Fuels 6.3 %, Materials Science 18.3 %, Physics 12.4 %, Chemistry 24.6 %.

Additional inferences can be made based on the facts supplied, such as the fact that the top producing nations in science concentrate their efforts heavily in the fields of chemistry, materials science, physics, electrochemistry, and energy fuels. Together, these five fields account for 51.5 % or more of the scientific output in these nations. This suggests that these disciplines place a lot of focus on research and development, which may be fueling advancements in science and technology in adjacent industries.

Chemistry and materials science are of great interest. They hold a major position in both the countries with the largest reserves and the countries that produce the most scientifically. These topics make up a sizeable amount of both divisions' scientific output, pointing to an emphasis on the investigation and development of novel substances, materials, and applications. Research concentrations in the aforementioned fields—chemistry, materials science, physics, electrochemistry, and energy fuels—are greater in the countries with the largest lithium reserves than they are among the top producing nations of science. This suggests that these nations are concentrating their technological and scientific efforts in fields directly related to lithium and its use in energy and new materials.

Given the growth of the fields of electrochemistry and energy fuels, which directly affect the creation and application of batteries and energy storage technologies, the interest in energy applications is noteworthy. It is present in both countries with significant lithium reserves and countries that are leaders in production science. This indicates a shared desire to advance renewable energy

Table 3
Top 20 countries regarding research and reserves cited in the key issues.

		Leading research countries			Leading production countries [a]		Gap
Ranking	**Topics Citation**	**Articles**	**%**	**Topics Citation**	**art prod**	**%**	
1	Lithium-ion Battery	39028	23,2 %	Lithium-ion Battery	5561	14,1 %	−9,1 %
2	Supercapacitor	27913	16,6 %	Lithium-sulfur Batteries	3439	8,7 %	−7,9 %
3	Lithium-sulfur Batteries	25653	15,3 %	Supercapacitor	3130	7,9 %	−7,4 %
4	Bipolar Disorder	4100	2,4 %	Bipolar Disorder	1751	4,4 %	2,0 %
5	Linbo3	3063	1,8 %	Linbo3	1463	3,7 %	1,9 %
6	Metalation	1779	1,1 %	Stars	768	1,9 %	0,8 %
7	Neutron Irradiation	1649	1,0 %	Metalation	682	1,7 %	0,7 %
8	Total Synthesis	1485	0,9 %	Glasses	563	1,4 %	0,5 %
9	Hydroboration	1276	0,8 %	Dentin	532	1,3 %	0,5 %
10	Ionic Liquids	1203	0,7 %	Ionic Liquids	418	1,1 %	0,4 %
11	Hydrogen Storage	1201	0,7 %	Neutron Irradiation	418	1,1 %	0,4 %
12	Star	1172	0,7 %	Ethylene Polymerization	390	1,0 %	0,3 %
13	Ethylene Polymerization	1120	0,7 %	Total Synthesis	379	1,0 %	0,3 %
14	Glasses	1119	0,7 %	Organic Rankine Cycle	325	0,8 %	0,1 %
15	Vanadium dioxide	1023	0,6 %	Bulk Modulus	322	0,8 %	0,2 %
16	Bulk Modulus	913	0,5 %	New Mineral	313	0,8 %	0,3 %
17	Oxygen Reduction Reaction	910	0,5 %	Tokamak	281	0,7 %	0,2 %
18	Tokamak	804	0,5 %	Geochemistry	277	0,7 %	0,2 %
19	Silicon Photonics	799	0,5 %	Hydrogen Storage	270	0,7 %	0,2 %
20	Dentin	753	0,4 %	Thermoluminescence	269	0,7 %	0,3 %
	Total	168111	100,0 %	Total	39439	100,0 %	

[a] Excluding leading countries in scientific research.
Source: Own elaboration based on WoS data.

Table 4
Main research areas, leading countries in research and leaders in production.

R	Research Areas	Leading research countries			Leading production countries 1		Gap
		Papers	%	Research Areas prod	Papers	%	
1	Chemistry	79382	25,4 %	Chemistry	15551	24,6 %	−0,8 %
2	Materials Science	67462	21,6 %	Materials Science	11554	18,3 %	−3,3 %
3	Physics	33240	10,7 %	Physics	7835	12,4 %	1,7 %
4	Electrochemistry	27439	8,8 %	Electrochemistry	4375	6,9 %	−1,9 %
5	Energy Fuels	24813	8,0 %	Energy Fuels	3989	6,3 %	−1,7 %
6	Science technology other topics	24516	7,9 %	Science technology other topics	3733	5,9 %	−2,0 %
7	Engineering	14581	4,7 %	Engineering	3086	4,9 %	0,2 %
8	Metallurgy Metallurgical Engineering	6334	2,0 %	Psychiatry	1821	2,9 %	0,9 %
9	Psychiatry	4720	1,5 %	Neurosciences Neurology	1695	2,7 %	1,2 %
10	Optics	4645	1,5 %	Optics	1507	2,4 %	0,9 %
11	Neurosciences Neurology	3841	1,2 %	Astronomy Astrophysics	1120	1,8 %	0,6 %
12	Nuclear Science Technology	3455	1,1 %	Metallurgy Metallurgical Engineering	1095	1,7 %	0,6 %
13	Polymer Science	3326	1,1 %	Nuclear Science Technology	1070	1,7 %	0,6 %
14	Pharmacology Pharmacy	2630	0,8 %	Pharmacology Pharmacy	920	1,5 %	0,7 %
15	Thermodynamics	2093	0,7 %	Biochemistry Molecular Biology	805	1,3 %	0,6 %
16	Environmental Sciences Ecology	2063	0,7 %	Thermodynamics	682	1,1 %	0,4 %
17	Biochemistry Molecular Biology	2040	0,7 %	Environmental Sciences Ecology	642	1,0 %	0,3 %
18	**Astronomy Astrophysics**	1846	0,6 %	Polymer Science	617	1,0 %	0,4 %
19	Crystallography	1781	0,6 %	Crystallography	556	0,9 %	0,3 %
20	Instruments Instrumentation	1774	0,6 %	Instruments Instrumentation	555	0,9 %	0,3 %
	Total	465614	100,0 %		11236	100,0 %	

Source: Source: Own elaboration based on WoS data. [1] Excluding leading countries in scientific research.

technologies and create more effective energy storage systems. However, it can be seen that there are significant gaps in the areas of Materials science (−3.3 %), Science technology other topics (−2.0 %), Electrochemistry (−1.9 %) and Energy fuels (−1.7 %), which shows the level of lag that countries that do not lead the scientific production present, in key areas in the coming years.

In the final analysis, the background suggests that the top nations for scientific production have a significant concentration in critical fields including Chemistry, Materials Science, Physics, Electrochemistry, and Energy Fuels. Greater intensity is shown in these regions in nations with significant lithium reserves, reflecting a particular concentration on research into lithium and its uses in energy and materials. These findings imply that in the context of scientific research and development, the need for energy and the availability of natural resources interact.

Lithium innovation and research encompass various types of advancements that contribute to the development and utilization of lithium in different industries. One type of innovation in lithium research is focused on improving lithium-ion battery technology. Researchers are constantly exploring ways to enhance the energy density, charging speed, safety, and longevity of lithium-ion batteries. This involves innovations in electrode materials, electrolyte compositions, cell designs, and manufacturing processes. By pushing the boundaries of lithium-ion battery technology, scientists aim to address key challenges and unlock new opportunities for energy storage applications, electric vehicles, and portable electronics.

Another type of innovation in lithium research pertains to sustainable lithium extraction and processing methods. Sustainable practices are being developed to minimize the environmental impact of lithium mining, such as reducing water usage, optimizing energy efficiency, and implementing responsible land reclamation. Additionally, researchers are investigating novel extraction techniques that can efficiently extract lithium from unconventional sources, including geothermal brines, oilfield brines, and lithium-containing waste streams. These innovations in extraction and processing contribute to the responsible sourcing and production of lithium, aligning with the principles of environmental stewardship and social responsibility.

Furthermore, research in lithium innovation encompasses the exploration of advanced lithium-based materials for various applications. This includes innovations in lithium-ion conductors, solid-state electrolytes, and lithium-containing compounds. Scientists are investigating materials that can improve the performance, safety, and stability of lithium batteries, as well as materials for other lithium-based technologies like supercapacitors and catalysts. By expanding the knowledge and understanding of lithium-based materials, researchers aim to discover new functionalities and optimize their properties for a wide range of applications, ranging from energy storage and electronics to healthcare and renewable energy systems.

In summary, lithium research and innovation span a wide range of research areas and topics of interest, including efforts in lithium-ion battery technology, sustainable extraction methods, and exploration of advanced materials through lithium based. These innovations contribute to the development of more efficient, sustainable and versatile lithium-based technologies. Continued research and investment in lithium innovation is crucial to driving advances in energy storage, transportation, and other industries, ultimately facilitating the transition to a cleaner, more sustainable future.

There are challenges that must be faced by the countries that have the main mineral reserves in the world and that, in light of our results, must be considered, differentiating those that already have a competitive advantage in the market and those that still do not. In the case of the former, since they have available financial resources given the production of the mineral, the use of resources for research and development should be a priority, and reduce the gaps in the identified areas, which would allow the possibility of adding value to the material at its origin, and with these give a plus of sustainability to the production of goods and services around lithium.

In the case of the latter, managing to develop the mineral extraction industry efficiently and sustainably over time will be a priority, particularly developing national policies regarding the mineral and making efforts to collaborate and attract foreign investment. Reaching the standards of producing countries is its main challenge, so investing in research and development in this direction should be a priority, both to increase national scientific production and to generate advanced human capital to make scientific collaboration viable. on an international level. As previously mentioned, scientific production by itself does not guarantee that countries can develop the industry competitively at the international level, but it is an unavoidable basic condition to achieve it. The development and utilization of lithium reserves are also influenced by other factors, such as infrastructure investment, political stability, government regulations, and industrial capabilities.

Therefore, these nations could take into account the importance of increasing their scientific and technological capacities through the promotion of regional research and development, international cooperation, and investments in infrastructure and human resources in the field.

To the extent that they can invest part of the proceeds from their sale in proactive development and innovation policies in the various sectors of mineral production and the value-added chain, this would allow them to diversify their economy and guarantee a more integral and sustainable lithium industry over time.

Creating appropriate policies and regulations can also aid in promoting investment in R&D, advancing the protection of intellectual property, and facilitating technological transfer. This includes fostering an atmosphere that encourages investment in scientific and technology ventures related to lithium. Parallel to this, encourage international collaboration with other nations who have expertise in lithium research and development. This could involve working together to develop specialist human resources, participating in international projects, and exchanging expertise.

Furthermore, as to basic scientific research, these nations should support the valuation and diversification of the lithium value chain by encouraging R&D in fields like battery production, electric mobility, energy storage, and other potential applications of lithium. This is necessary because these challenges will require sources of funding.

Countries will need to make a sustained commitment to addressing these issues, and government, academia, business, and other relevant stakeholders will need to work closely together. By overcoming these difficulties, nations will be able to maximize the use of their lithium supplies and establish themselves as industry leaders in the study and development of this important mineral.

Its limitations must be taken into consideration when generalizing the findings, as with all studies. For instance, the bibliometric analysis did not consider all existing databases that index scientific papers, like Scopus and others. The distribution of research efforts at the topic area level can be better estimated with the addition of these kinds of additional databases.

5. Conclusions

According to the investigation, China and the United States, which together accounted for 41 % of all publications during the time period under consideration, are the top producers of lithium-related scientific research. Due to their strategic advantage in natural resources and scientific knowledge linked to lithium, these nations are able to shape the worldwide market and have a big impact on sectors like electric transportation and rechargeable batteries.

Other nations with sizable lithium reserves, such as Australia, Chile, and Canada, also play an important role in scientific research. In terms of natural resources and scientific understanding, these nations hold a leadership position and play a significant role in the lithium sector.

Despite not playing a substantial role in the production of the material, nations like Germany, Russia, and Spain have lithium reserves and pertinent scientific output. These nations can play a significant role in the energy and electric mobility industries thanks to the advantage of natural resources and the innovation they are fostering in sectors related to lithium.

Some nations that have sizable lithium reserves, such as Bolivia, Argentina, and Chile, only have a little presence in scientific research. This suggests a heavy reliance on resources and expertise from outside sources. To assure a more comprehensive and long-lasting participation in the sector, these nations could gain from enhancing their scientific and technological capabilities in the area of lithium.

Potential that is untapped exists in nations having lithium reserves who are not involved in the production of the mineral or pertinent scholarly work. To fully utilize its potential for natural resources, these nations may take into consideration the need for investment, capacity building, international collaboration, and economic diversification in the lithium business.

Regarding the knowledge gaps, it is shown that research into lithium-ion batteries is prioritized by both nations with major mineral reserves and those with the highest levels of scientific production. The level of research varies in other areas, demonstrating that each group of nations has a different approach and set of goals.

Furthermore, it can be argued that the nations with the largest lithium reserves and the top scientific producers are crucial to the lithium market. However, it is crucial to boost technological and scientific capabilities, encourage international cooperation, and reorient the economy toward the lithium sector if it is to fully fulfill its potential and maintain a dominant position over the long term. To enable the effective manufacture and commercialization of lithium-related products, additional elements like infrastructural investment, political stability, and industrial capacities must also be considered.

The largest lithium deposit holders who do not contribute considerably to the scientific research on this mineral confront several difficult problems. Developing technological and scientific capabilities, establishing and bolstering organizations for scientific research and development, and investing in the education of scientists and lithium specialists are a few of these issues. This suggests that specialist education and training programs should be developed, and that it should be encouraged to work with international institutions and authorities. Encourage development and research. advancing lithium-related scientific study and technology advancement. To support innovation and knowledge transfer, this entails sponsoring research initiatives, establishing centers of excellence for research and development, and encouraging collaboration between government, industry, and academia.

Including this information would help to determine where the research efforts are focused, whether towards development at the basic level of use, or towards technical development that allows a greater added value. On the other hand, scientific production is estimated based on the number of scientific articles that have been developed on the subject, leaving out other relevant scientific products like patenting, which reflects technical progress surrounding the mineral resource. Future research can strengthen these areas to have a better grasp of how research efforts around lithium are dispersed, the discrepancies between the leading nations in scientific production and the countries that have the primary lithium reserves.

Finally, and from the standpoint of public policy, this research attempted to highlight the disparities and gaps in knowledge generation between leader research and producer countries; this represents an opportunity to rethink these policies using existing knowledge and promoting collaborations between mining and technology companies, in order to develop a more sustainable, efficient, effective, and competitive industry with future societies.

Ethical approval

The manuscript in part or in full has not been submitted or published anywhere.

Consent to participate

The manuscript does not report on or involve the use of any animal or human data or tissue.

Consent to publish

The Author consents to publication of the Work in the journal.

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Availability of data and materials

The data that support the findings of this study are available from the authors, upon reasonable request.

CRediT authorship contribution statement

Cristian Colther: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Claudia Pezoa-Fuentes:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Data curation. **Jean Pierre Doussoulin:** Writing – review & editing, Writing – original draft, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Claudia Pezoa-Fuentes reports was provided by Austral University of Chile–Campus Isla Teja. Claudia Pezoa Fuentes reports a relationship with Austral University of Chile–Campus Isla Teja that includes: non-financial support. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1

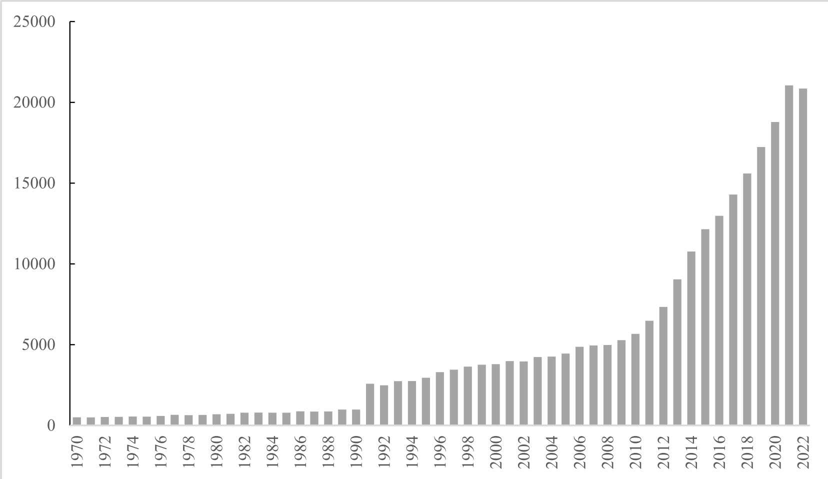

Fig. 6. Evolution of the number of lithium-related scientific articles (1970–2022).
Source: Own elaboration based on data from (WoS 2021).

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