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Lithium- Ion Battery

Evolution of Available Scientific Publications and Future Research Trends

Andrea Duarte da Cruz

Dissertation Proposal report presented as partial requirement for obtaining the Master's degree in Statistics and Information Management

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LITHIUM-ION BATTERY

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by

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Dissertation Proposal report presented as partial requirement for obtaining the Master's degree in Information Management, with a specialization in Risk Analysis and Management

Advisor / Co Advisor: Bruno Damásio / Sandro Mendonça

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ABSTRACT

Climate changes awareness has gained more visibility over the past years and new ways of dealing with them are on demand. Lithium-ion battery research is one of contributors to this technological innovation to overcome carbon-based source of energy, due to their excellent performance and long cycle life.

This paper aims to apply a bibliometrics analysis to track the existing scientific publications on lithium-ion battery research without timespan restrictions. From Web of Science (WoS) a total of 65154 publications are retrieved belonging to the refined keywords that are present in publications Title, Abstract and Keywords.

In order to analyze the dataset, a bibliometric analysis will be presented regarding the construction of networks based on the keywords co-occurrence, co-authorship, co-cited references and distributions of publications over geographical regions, institutions, scholars, and categories contributions. From this network, an overall view of the output dissemination of scientific publications made about this domain will be developed.

A bibliometric analysis on lithium-ion battery is assessed by means of quantitative and visualization tools using R and VOSviewer software. The results obtained are evaluated and summarized from the perspective of total annual publications, countries, institutions, authors, terms, journals and subject categories. This analysis illustrates the role of collaborative partnerships in successful scientific research on lithium-ion battery, with China contributing the most to knowledge production with a total of 33318 publications, 15 of 20 most productive institutes, 12 of 20 most prolific authors and 3 of 10 most cited articles. China and US have the strongest relationship when it comes to collaboratives papers with 3087 co-authorship articles. Tsinghua University in China is the most productive institute with 1393 articles and Nanyang Technology University in Singapore is the most influential institute with 243 citations. Journal of Power and Sources has published the most articles among all the journals, having a total of 6104 publications.

The process of analyzing and evaluating scientific production and the results obtained, are expected to contribute to an overview of the trajectory of the research on lithium-ion battery, highlighting main actors leading knowledge production on this domain and assess new trend topics that can help in future research.

KEYWORDS

Lithium-ion battery; Bibliometrics analysis; Climate changes

INDEX

Figure Index

Table Index

1. INTRODUCTION

Scientists predict that average temperature will increase by 2.5°C in the next century resulting from the continuous human activities that are one of main responsible for the emission of harmful gases [1]. Climate changes led to a growing number of meteorologic phenomena like hot waves, droughts and floods that conducts to a huge impact in the natural ecosystems and in the human health. Overcome or dimmish the consequence of global climate changes, it may be one of the most important and painful challenges to human beings can accomplish.

The awareness and interest for climate changes grew up in the past decades and headed with development of international agreements like the Kyoto Protocol or the Paris Agreement. The major aim to stop the average temperature increase till the end of the 21st century promoting the creation and implementation of policies, investment in new technologies to help mitigate the climate changes and promote negotiations with the objective of raising financial funds to achieve the goals established [2].

Despite the agreements settled, huge volume of studies and research worldwide were developed independently or in collaboration, representing an effort to develop new technologies and policies to achieve new and renewable sources of energy to combat the carbon- based ones. Renewable energy policies vary broadly, both in terms of the technologies and energy sources they include, as well as in terms of the policy instruments that support them [3].

In 1970, after the oil crisis in that decade, Mr. Stanley Whittingham proposed for the first time the use of LIBs that are a type of rechargeable batteries composed by four primary elements: anode (most commonly carbon), cathode (typically as a lithium metal oxide), electrolyte (lithium salt dissolved in an organic solvent mixture), and separator (a thin layer of porous polymer) [4]. The LIBs cells process of charge and discharge it is known as "rocking-chair" because of the movements of the lithium ions batteries make back and forth between the anode and cathode during the charge- discharge cycles [5].

In 1991 Sony commercialized the first Lithium-ion battery and since then, LIBs being playing an important role in modern society as renewable source of energy and become used in portable electronic devices like: cellular, laptops, digital cameras, portable game machines and portable audio players. In recognition of this importance, the 2019 Nobel Prize in Chemistry was awarded to Mr. Stanley Whittingham, John B. Goodenough and Akira Yoshino for "the development of lithium-ion batteries" that created a rechargeable world [6].

2010 marks the boom of the electronic vehicles (EVs) market and once again LIBs gain more visibility with an increasing in the number of batteries production resulting from the growing demand, since most of these EVs uses LIBs in place of fuel used in combustion engine. It is expected that the LIBs production will continue to increase in the next years. Some scholars predict that the LIBs market would increase from 40.1 billion dollars in 2021 to 116.6 billion dollars by 2030 [7].

Another problem that raises from the increasing number of LIBs production, is what to do with the physical battery and their components when it loses its usefulness which life to give to this precious material. In fact, the recycling of retired cells has important significance towards metal resources [8][9], ecological environment [10] and even state security. Innovative process design and methods had continually been tried to improve the recycling efficiency [11][12] and reduce the effects on environment [13]. Although these processes exist and are in use, it is obvious that there are still many difficulties about recycling methods remained to be solved when huge amount of spent LIBs is arriving [14]. But many current studies are still in the experimental stage [15] and certainly these studies will continue to evolve since LIBs production presents a rising tendency.

For almost 30 years of publications on LIBs, a large data frame with more than 65100 observations from scientific publications were assembled having the retrieval formula mentioned in the Title, Abstract and Keywords of authors publications. This allows to analyze and construct meaningful interactions and relationships among all the observations and address research questions like: What actors are leading the dissemination of LIBs? Which geographical area/institutions are more prolific in terms of publications? What kind of future trends/patterns and challenges LIBs will have? Answering these questions can acknowledge a more instinctive picture of evolution on LIBs and future research trends.

1.1. PROBLEM JUSTIFICATION

Nowadays when it comes to environment concern, a lot of information and policies are being created to bring awareness worldwide so society can have access to different technologies that can help to diminish or overcome problems related with climate changes. Scientific production it is one of the most important allies in this process of technological transformation, since a lot of new technologies have been developed with the main objective of finding new ways of renewable source of energy and optimize the existing ones.

Lithium-ion batteries (LIBs) are one of those technologies that arised as an alternative source of energy to carbon-based one, especially on the mobility sector. LIBs play an important role as a motor of energy transition and a promotor of circular economy as it can attract more popularity by its sustainability and change the consumption habits and promote an economic and environmental remaking [16].
The high energy efficiency of LIBs may also allow their use in various electric grid applications, including improving the quality of energy harvested from wind, solar, geo-thermal and other renewable sources, thus contributing to their more widespread use and building an energy-sustainable economy. Therefore LIBs are of intense interest from both industry and government funding agencies, and research in this field has abounded in the recent years [17] LIBs have an unmatchable combination of high energy and power density, making it the technology of choice for portable electronics, power tools, and hybrid/full electric vehicles.

As consequence of all the studies developed, an enormous volume of scientific productions has been produced and being spread around globe by different geographical location, authors and institutions. Bibliometric analysis has already been applied to LIBs field, those studies were developed to understand the LIBs physical and chemical components evolution through years and some research intend to understand LIBs evolution and trends within a specific time period.

1.2. RESEARCH OBJECTIVES

Bibliometric analysis has already been applied to LIBs field but was not used to analyze the spread, evolution and dissemination since the first studies available about the topic until nowadays. With a continuous development and production of data about the use of LIBs, this study will apply a bibliometrics analysis to evaluate the existing literature about LIBs and try to understand the distribution of papers per countries, institutions, scholars and forecast the research trends. With the aim of highlighting the main geographical areas, institutions, and authors responsible to spread and contribute for the dissemination worldwide of LIBs studies.

An R-tool, Bibliometrix package supports scholars in three key phases of analysis: data importing and conversion to R format, bibliometric analysis of a publication dataset, building matrices for co-citation, coupling, collaboration, and co-word analysis. Matrices are the input data for performing network analysis, multiple correspondence analysis, and any other data reduction techniques [18].

The main goal of this study is to conduct bibliometric research to evaluate the available scientific publications on LIBs. By identifying the most productive authors, institutions and geographical areas it is possible to understand LIBs evolution through years and forecast future research trends.

The rest of the paper is structure as following. Section 2 brings a summary of the existing literature on LIBs published bibliometric studies. Next, in section 3 the paper explores the data with a resume of the data retrieved and transformations made to have the final dataset ready for bibliometric analysis. The paper than explains what the research consists of and also the process of conducting a bibliometric analysis and the basis needed to perform the analysis. Furthermore, section 4 presents the main remarks of the analysis results followed by the conclusion section of this study.

2. LITERARURE REVIEW

Due the growing number of scientific publications about LIBs, a great amount of literature about the topic is available. These publications mainly focus on the evolution of the LIBs components and the dissemination of its use in a modern society. During the writing of this study, a lot of different publications were read in order to understand the context of LIBs in terms of scientific publications and the evolution through years of this topic.

Many of the publication's emphasis on the chemical and physical processes that LIBs had to pass until be a stable source of energy that can be commercialized in large scale and can be used in most of modern processes of researchable source of energy. Recently another category is presenting rising patterns on LIBs scientific production: environment. This category uses quite often the scientific production and evolution of LIBs as a great contributor to help mitigate the climate crisis caused by fossil source of energy and the continuous human activities.

When it comes to bibliometrics analysis applied to the research trends and evolution of Lithium-ion battery, there is no extensive literature that aim to track the emergence of this topic and who is leading these processes of scientific, technological and social transformation. Despite this existing gap, there are already some studies that used bibliometrics to forecast LIBs research trends globally but restricted to a specific period and came to interesting findings.

A recent study using patents as indicator, as explored battery market from 2000 to 2019 to construct a worldwide map patent of battery sector and concluded that the majority of battery patents have origin in Asia and several Asian and European countries had their battery patenting activity increased during the referred timespan. Through the study period, is to highlight that some batteries technologies gained visibility and interest and one of them is LIBs [19].

The bibliometrics analysis conducted by Lin using the period 1993-2008 [20] is one of few studies that aims to trace LIBs trajectory in modern society and translate the contributions that have being made by scholars, institutions and countries and also try to find a future pattern in the topic evolution.

Lin [20] emphasize the increasing of cumulative number of papers in the 16-year study period and the 3 major geographical areas that were leading the scientific production by that time: north America, western Europe, and eastern Asia. Regarding the publications per institutions, five Chinese institutes were included in the top ten institutes with the greatest number of publications. By contrast, the top ten institutions with the greatest number of citations per publication contained four institutions from the United States but no institution from China. This phenomenon shows that while China has produced the greatest quantity of papers on lithium-ion battery research, the quality of publications from institutions in China requires improvement [20].

Concerning the statistical analysis of publications from WoS and the developing tendency of the recycling methods of spent LIBs, a 10-year study that consider the period 2008-2018 revealed the importance that this topic has gained in past years and the main countries, institutions, and scholars responsible for the academic production that influenced this field [21].

According to the data, China has 204 publications, accounting 53,26% of total papers published, South Korea 37 articles with 9,66% of total publications and Brazil with 32 published papers with 8,36% of global publications. These are the top three countries, followed by US with 31 publications, India having 22, Australia and Japan 14 publications, and other ones are responsible for most of the data collected, analyzed, and published. Following the result data, when it comes to productivity China is the number one country producing scientific data about this topic and the same for cooperative works what makes Chinese researchers the most influential and represents more than half of the academic publications made during the period of the study [21]. When analyzing the scientific production from the authors point of view, once again Chinese scholars and researchers are the ones with more publications made followed by Brazil, South Korea, and US [21]. The proportion of participant areas in Asia, America and Europe is severally 79,37%, 18,02% and 13,05%, respectively. China, South Korea, and Japan have obvious advantages in the manufacturing of LIBs. So, it is not difficult to understand that these countries tend to start earlier and play more positive parts in the research about the recycling methods of spent LIBs [22]. In terms of total quantity, research institutions from China and South Korea have filled out the top positions. They are Beijing Institute of Technology 25 papers what represents 6.53% of total publications, Central South University with 23 papers and 6,01% of total papers published and Korea Institute of Geoscience and Mineral Resources with 22 articles accounting 5,74% of publications made [21].

On the basis of bibliometrics results from the 10-year study is to highlight that China has 53,26% of total papers published and South Korea 9,66%, are the leading countries in this domain. Central South University has 7,14% of published papers and Beijing Institute of Technology 9,61% in China is the most productive single and cooperative institutions, respectively [21].

A study about LIBs research in India during 1989 to 2020, evaluates the LIBs assessment in India market as a new source to gradually phase out fossil fuel based vehicles and replace them with electric vehicles (EVs), indicates that the annual scientific production of papers increased in the 32-year study and shows a rising trend. The Citation Per Paper among the 4 more prolific institutions was about 18 [22] and Indian researchers engaged in Li-ion battery research have collaborated with authors from 59 other countries, however, Indian authors had only 12 out of 988 internationally collaborative research papers with China who is the leading country in the world in the field of Li-ion battery research [22]. Keywords analysis suggests that the research emphasis keeps changing over different time periods, Supercapacitor, graphene, electrochemical performance and EV received attention during the latter half period of the study and moved up the rank [22].

When it comes to research trends of LIBs since early days till nowadays, the literature available is not so extensive as it is regarding the evolution of the LIBs physical and chemical components. Most of the literature concerns with LIBs energy storage and the materials used for thermal management using bibliometrics analysis. Despite the few literature, there are already some interesting studies that forecast the LIBs trends and future patterns applied to a specific time period and geographic area. Concerning the track, analyze, predict, and forecast who is in the front line of this social challenge and future research trends with no limitations when it comes to timespan, it seems to be an extensive explored field. I could not find literature that uses no restriction in terms of timespan to produce studies aiming to path who is transforming the battery sector and understand the LIBs technological trajectory trough years.

3. DATA AND METHODOLOGY

To construct a structured data frame about a topic, a basic unit of research it is a primary need, and this basic unit is achieved by the scientific production of a large number of researchers and scholars grouped by common topics. To acquire this data frame on LIBs using bibliometrics analysis, the representative and relevant documents need to be found, collected, extracted, and analyzed to conduct this study.

3.1. DATA

Documents are collected from Web of Science (WoS) which is one of the globally well-known index databases and collects high-quality bibliographic information about publications in a wide range of scientific disciplines [23]. WoS collects and records scientific publications with high quality about varied range number of different topics organized by field of study, authors, regions, institutions, year of publications, citations and so on.

The data are retrieved following the retrieval formula (TS = "lithium ion batter*" or TS = "lithium-ion batter*" or TS = "li ion batter*" or TS = "li-ion batter*") which are the usually used expression of LIBs, and they were used to identify the topic presence in the Title, Abstract and Keywords of publications. The database was retrieved on July 03, 2022 and consider all the publications with occurrence of the retrieval formula in papers due in 2021, since 2022 was not counted for being an incomplete year. The document type is filtered to article, which represents a total of 68285 publications retrieved.

Based on statistical analysis, research trends about LIBs can be traced after the data being “clean” without values that can cause noise during the analysis, such as keywords that are not present on the retrieval formula, what ensure that the final dataset has no false positives and guarantee that all publications meet the document type defined.

3.1.1. DATA TRANSFORMATION

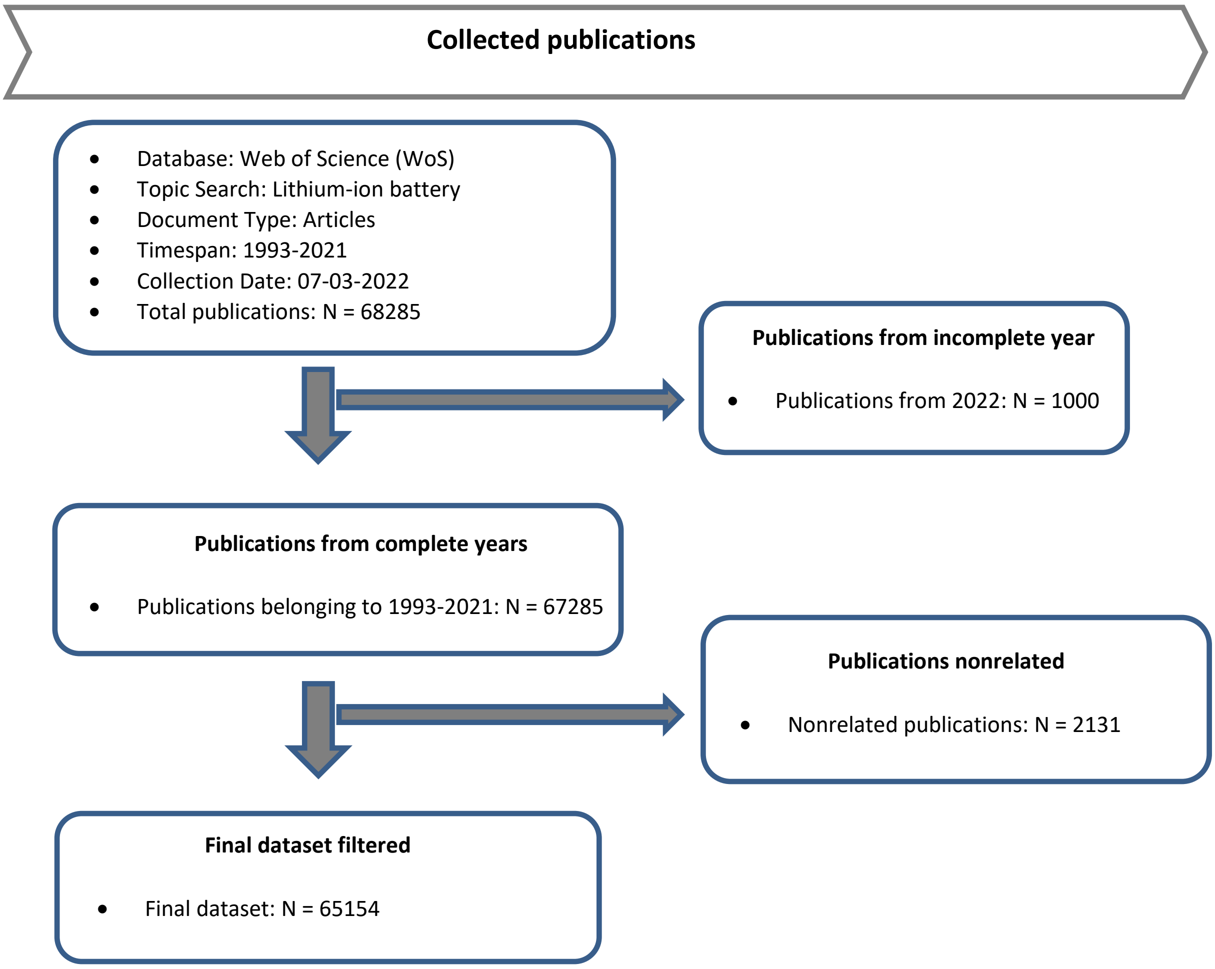
To better understand the dataset and the variables behavior, an initial exploratory analysis is an essential step to start the study. This can provide an overview of the data and some uncommon patterns can be spotted like presence of missing values in variables, data not belonging to timespan break point, and false positive observations from the retrieved data.

In order to have a clean dataset to start exploratory analysis, some standardizations were made with some variables: the keywords columns had some missing values and since these columns are important to perform keywords evolution analysis, the missing values were treated.

Analyzing the presence of false positives is also an important step on data cleaning since all the observations should meet the retrieval formula in Title, Abstract and Keywords of publications. To be easier to conduct this analysis, the presence of false positives was made through category groups where for each category a review was made in order to identify and eliminate observations that did not met the retrieval formula and were false positives on the dataset. Some of the data collected were referent to 2022 and a break point was established in 2021 for being the last complete year with available publications on LIBs, so the observations from 2022 were completely removed from the final.

After having the dataset refined as much as possible, the first analysis made to the data collected was a descriptive analysis to have a brief understanding and overview of the data distributions based on: data count, average, proportions, ranks, etc. For better understanding and support the primary descriptive analysis carried, summary statistics of data were computed, and the graphs generated as outputs of interaction between the dataset observations.

Figure 1- Data collection and cleaning



The final dataset contains a total of 65154 articles that mention retrieval formula in the Title, Abstract and Keywords on the period analyzed. The publications were made by 60210 different authors from 96 countries published in 1320 different sources.

3.2. METHODOLOGY

Research represents a way complex activity that can be conducted in a variety of activities and environments. Research is responsible to track and find measurables ways to express the production of knowledge resulting from studies, collaborations and interactions between authors and the environment that they are included, what leads to creation of indicators. Indicators facilitates the reading and interpretation of knowledge production. Research is responsible for adding new knowledge to existing store and for redefining problems, formulating hypothesis or suggested solutions; collecting, organizing and evaluating data; making decisions and reaching conclusions; and at last carefully testing the conclusions to determine whether they fit they fit the formulating hypothesis [24].

Research activity can be split into three main categories: input, output and impact. Input indicators are based on the resources and investments that fuel scientific activities. Common input indicators include the size and other characteristics of the scientific workforce as well as funding allocated to research.
Output indicators measure the knowledge that is produced as a result of that input: typically, publications and patents. Impact indicators measure the ways in which scholarly work has an effect upon the research community and society [25].

Since there are an enormous number of fields that are object of studies, and these fields generate its own data, the measurement of research and consequently its own indicators, a unique pattern about a specific field is created. Indicators produced can be applied to other studies or used to bring out insights about a field of study. The scientific publications are the basic unit of the intellectual structure of any research domain, and they are produced through the concerted effect of a large community of researchers and grouped by way of related subjects [26].

Bibliometrics is a kind of research method which is used to analyze the connections among samples by counting the items above and the development tendency of a specific topic could be concluded [27] [28] through this way. Despite highlighting the connections among samples, bibliometrics facilitates on finding research patterns about a topic, collaboration between countries, institutions and authors. It contributes to find and describe the contributions and future research patterns in a specific area of study.

The term bibliometrics as we know, was first introduced in 1969 by Alan Pritchard on an article entitled "Statistical Biography or Bibliometrics?" substituting the previous term Statistical Bibliography proposed by Hulme in 1923 [29]. This term translates the application of statistical and mathematical methods to books and other media of communication.

In bibliometrics early stage, laws were defined to have a more structured view about the forecasting of the creation of behavior patterns in the scientific production and its authors. The mathematical and statistical methods used in bibliometrics are based on three typical models: Lotka's law, Zipf's law, and Bradford literature dispersion law. The bibliometric laws of Zipf, Bradford, and Lotka are the pillars of bibliometrics, scientometrics and informetrics [30].

Lotka's Law also known as the reverse square law, intends to highlight the productiveness of an author by taking in account the number and frequency of its publications in a specific field of study. According to Lotkas' law of scientific productivity only six percent of the authors in a field will produce more than 10 articles. Lotka's law when applied to large bodies of literature over a fairly long period of times, can be accurate in general, but not statistically exact. It is often used to estimate the frequency with which authors will appear in an online catalogue [31]. Lotka's Law is given by following formula:

$$X^n Y = C$$

Where:

- X is the number of publications
- Y is the number of authors with X number of publications

- n is a constant
- C is a constant

Zipf's Law or the Law of minimum effort, aims to predict the frequency and relationship of words within a large text. If you list the words occurring within that text in order of decreasing frequency, the rank of a word on that list multiple by its frequency will equal a constant. The equation for this relationship is:

$$r * f = k$$

Where:

- r is the rank of the word
- f is the frequency
- k is the constant

Zipf's illustrated his law with an analysis of James Joyce's Ulysses. He showed that the tenth most frequent word occurred 265 times, the two hundred word occurred 133 times and so on. Zipf's found, then that the rank of the word multiplied by the frequency of the word equals a constant that is approximately 26,500. Zipf's law again is not statistically perfect, but it is very useful for indexes [31].

Bradford's Law or the dispersion law, was introduced in 1948 by Samuel Bradford that proposes that in a specific field of study a small number or journals will be specialized in that field. This means that, in each subject area, a small number of journals account for a sizeable portion of the total publications in that area, that produces approximately one third of the articles [31]. From Bradford's Law, journals can be divided in three parts, each one with the same number of articles and the number of journals in each group is proportional to $1: n: n^2$, where n is a multiplier.

A bibliometrics analysis can be applied to any topic, its only necessary to collect and store publications about a given field. The first step to start the study is to have a clear topic definition. If the aim is to describe productivity in a given area, we must be sure that the documents included in our study are truly representative of the research field. As such, the documents gathered have to cover the whole domain of the field being analyzed [32].

Before gathering the data needed to conduct bibliometric analysis, scholars will need to define search terms in a way that will yield search results that is large enough to warrant bibliometric analysis and yet focused enough to remain in the dedicated research field or the scope of study specified in the first step [33].

Bibliometrics analysis has as output the retrieval publications quantitatively displayed and the interactions among the elements are presented in a visualization way. The extracted dataset is composed of the peer-reviewed publications, which are considered to be "certified knowledge" with universal credibility [34].

Bibliometrics arises as a new research discipline capable to track the origins, spreadness, dissemination, evolution and measure the indexes and indicators productions of a scientific field through the application of quantitative and statistical methods.

Currently, bibliometrics has an important role as a research tool since it can be applied to an extensive field of studies, not being restricted to just scientific universe. It is to be hoped that this term bibliometrics will be used explicitly in all studies which seek to quantify the processes of written communication. Bibliometrics studies has enormous capabilities to analyze, highlight and report important findings in publications and at the same time it is a key factor to forecast future patterns on the field's development and authors publications. Bibliometric methods estimate how much influence or impact a selected research article has on future research [35].

3.2.1. DISSERTATION DESIGN

Considering the goal of this study, the methodology applied is bibliometrics and based on a group of keywords that represents the retrieval formula on topic of LIBs, a meaningful set of publications were assembled allowing further analysis on LIBs scientific available publications.

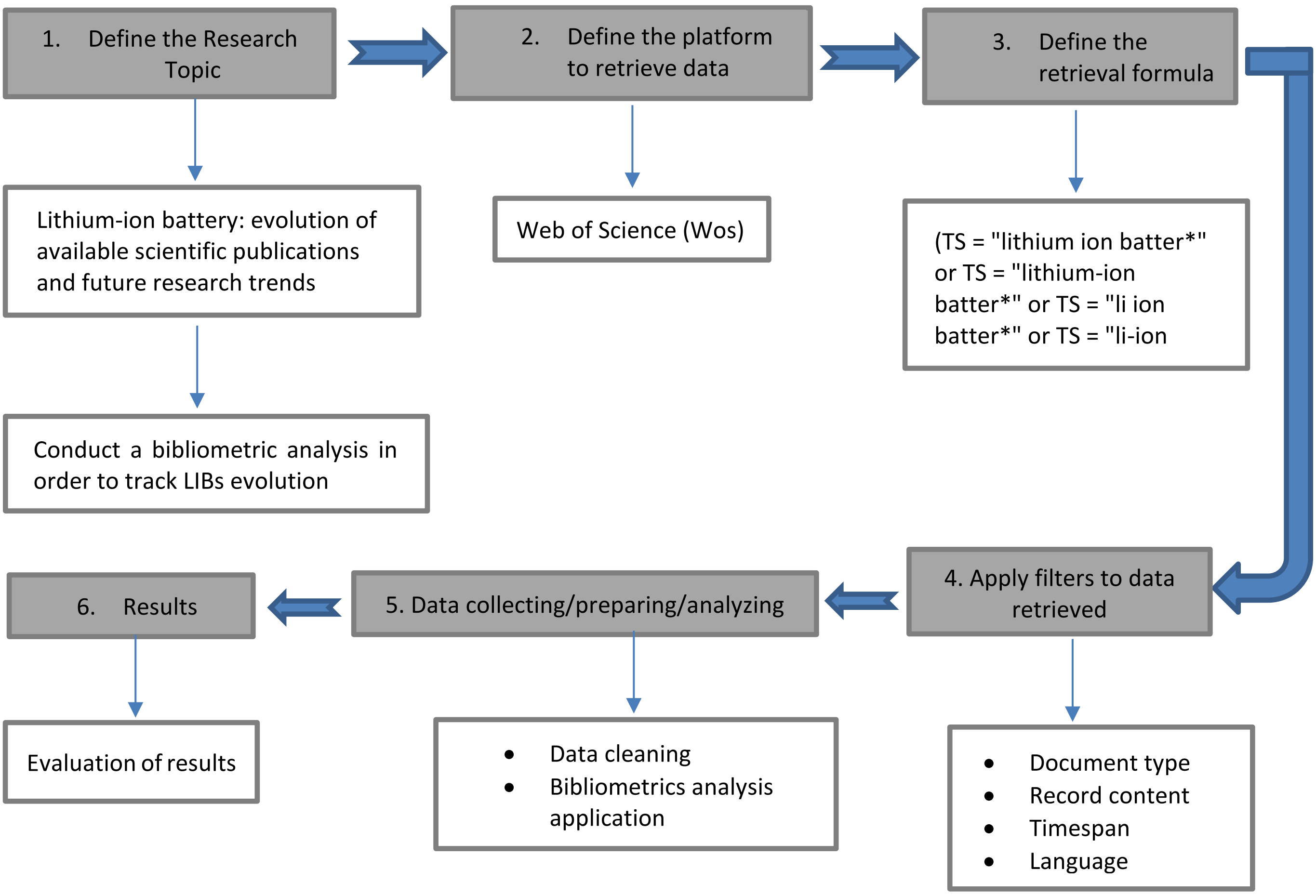
The constructions of a meaningful basis passes through different stages: defining the topic/field and the questions to be answered by the study, pick a well-structure platform to retrieve the data, create the retrieval formula based on common expression on topic, apply different filters on publications gathered from the retrieval formula to meet study goals, and save the data in a compatible format to be used on analysis tool.

Publications selection

To obtain the final set of observations, different filters are applied to publications to make the inclusion and exclusion of articles:

- Filter document type to articles
- Record content with full record and cited references
- Filter articles published until December of 2021
- The articles language as to be "English"

Figure 2- Dissertation design



After data collecting, it is necessary to prepare the data for analysis and this stage can be considered the main one. Since preparing the data involves cleaning observations that may not meet the study goal and can cause “noise” if not deleted from dataset. Once data cleaning is done, the dataset is ready for analysis, where a set of quantitative measures are applied, and then the evaluation/discussion of the results can be made based on quantitative and visualization data.

4. RESULTS AND DISCUSSION

In this section, the results achieved by the mean of methodologies described on previous chapters are analyzed and the most important information obtained are highlighted in terms of: annual publications, geographical distribution, institutes contributions, authors productivity and influence; most frequent research terms; different subject categories evolution and the most prolific publications sources.

4.1. Annual publications

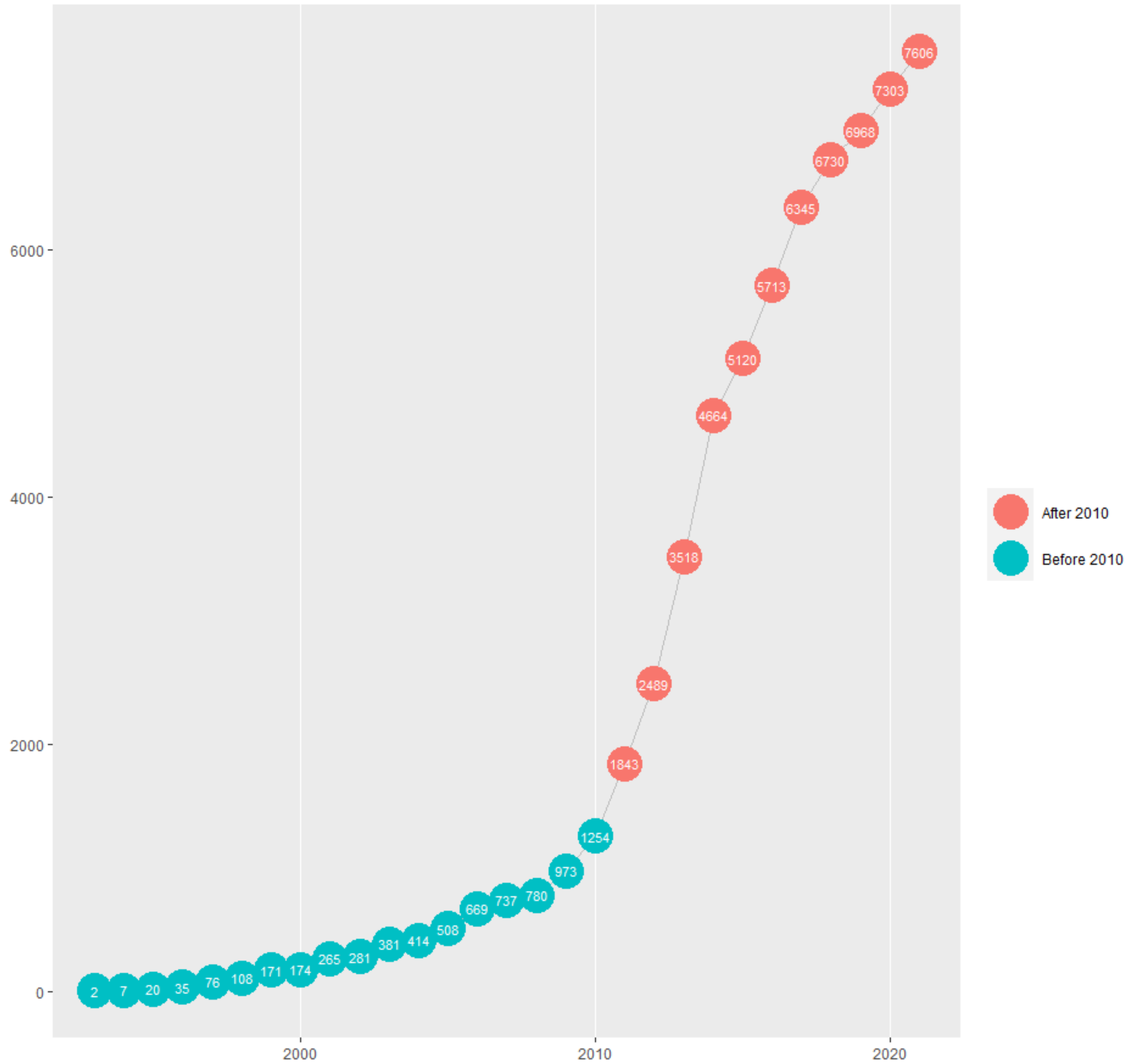
The annual evolution of publications outputs on LIBs are listed on Table 1. Starting with two publications in 1993 what is a subsequential period after Sony commercialized their first LIBs with success in 1991. The annual number of research published increased from this minimum to 7606 in 2021. Figure 3 shows for the study period considered that the cumulative number of publications per year increased and there are two periods to consider before 2010 and after 2010. It is clearly from 2010 forward that number of papers published consistently improved. This event might be related with the fact that was in 2010 that the VEs had started a massive production due to issues related with climate change and global warming and the battery technology used to run this type or vehicle are based on LIBs.

The global rate of adoption of light-duty EVs (passenger cars) has increased rapidly since the mid-2010s, supported by three key pillars: improvements in battery technologies; a wide range of supportive policies to reduce emissions; and regulations and standards to promote energy efficiency and reduce petroleum consumption [36]. From the articles distribution on the dataset, it can be observed that 89.47% of knowledge production was made within 2010-2021. Following the trend listed in Figure 1, annual number of research publications on LIBs may continue with this rising pattern.

Table 1 - Annual production of research on LIBs

Year	Number Publications	Cumulative Number of Publications
1993	2	2
1994	7	9
1995	20	29
1996	35	64
1997	76	140
1998	108	248
1999	171	419
2000	174	593
2001	265	858
2002	281	1139
2003	381	1520
2004	414	1934
2005	508	2442
2006	669	3111
2007	737	3848
2008	780	4628
2009	973	5601
2010	1254	6855
2011	1843	8698
2012	2489	11187
2013	3518	14705
2014	4664	19369
2015	5120	24489
2016	5713	30202
2017	6345	36547
2018	6730	43277
2019	6968	50245
2020	7303	57548
2021	7606	65154

Figure 3 - Number of publications per year



4.2. Geographical Contribution

From the analysis made based on the first author's affiliation, the selected articles from the dataset have the geographical distribution based in 96 different countries, and the top 30 most prolific countries have a total of 63426 publications made.

From the Table 2, China ranks in first place in terms of maximum number of publications with 33118 articles, representing 50,8% of total publications made. Followed by US with 7734 papers accounting for 11.8% of total publications. From Table 2 it is perceptible how knowledge production on LIBs is very asymmetric with China accounting half of the academic work produced on the considered period, together with US it represents 62,6% of the total articles published.

Most of the publications on the selected dataset were from single country publications (SCP) and led once again by China and US, with 27795 and 5928 publications, respectively. Australia, Israel and Pakistan had more papers having origin in multiple country publication (MCP) with a MCP ratio of 0,523 and 0,520, 0,622, respectively, which indicates the level of international collaboration of a country.

Table 2 - Top 30 countries with greatest number of publications

Country	Total Publications	Percentage Contribuitons (%)	SCP	MCP	MCP Ratio
China	33138	50,8892	27795	5343	0,161
US	7734	11,8769	5928	1806	0,234
South Korea	5230	8,0316	4319	911	0,174
Japan	3059	4,6976	2670	389	0,127
Germany	2602	3,9958	1974	628	0,241
India	1767	2,7135	1359	408	0,231
France	1216	1,8674	824	392	0,322
Canada	1095	1,6816	648	447	0,408
Singapore	910	1,3975	551	359	0,395
UK	833	1,2792	481	352	0,423
Australia	796	1,2224	380	416	0,523
Italy	581	0,8922	373	208	0,358
Spain	545	0,8369	326	219	0,402
Russia	477	0,7325	375	102	0,214
Sweden	442	0,6788	270	172	0,389
Iran	432	0,6634	354	78	0,181
Switzerland	364	0,5590	223	141	0,387
Turkey	346	0,5313	284	62	0,179
Poland	306	0,4699	241	65	0,212
Israel	271	0,4162	130	141	0,520
Belgium	244	0,3744	146	98	0,402
Netherlands	185	0,2839	108	77	0,416
Malaysia	167	0,2563	106	61	0,365
Austria	158	0,2425	96	62	0,392
Brazil	150	0,2302	125	25	0,167
Denmark	117	0,1795	62	55	0,470
Pakistan	111	0,1703	42	69	0,622
Ireland	105	0,1611	75	30	0,286
Norway	100	0,1534	63	37	0,370
Finland	95	0,1458	61	34	0,358

Abbreviations: SCP, single country publication; MCP, multiple country publication

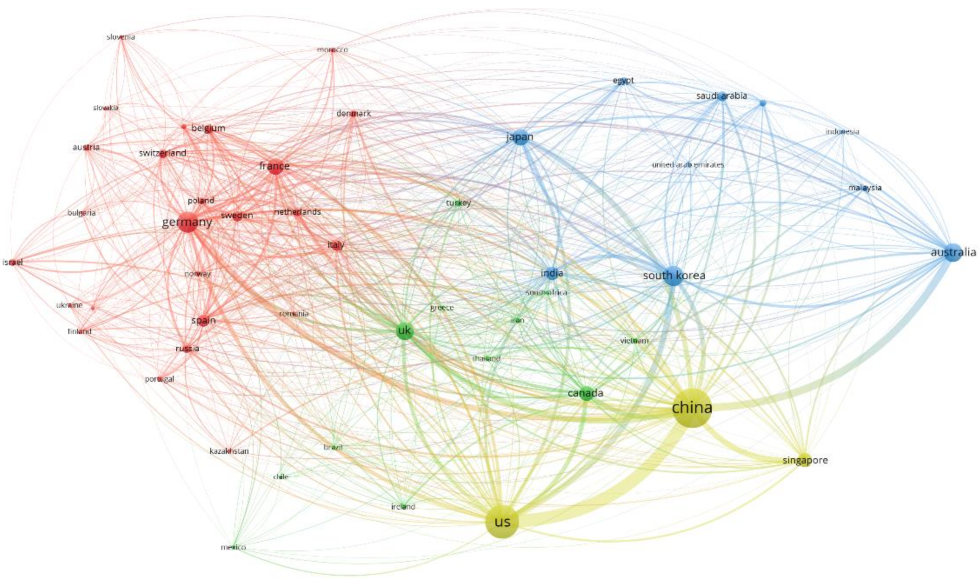
Table 3 – Top 30 countries with greatest number of publications per 1M habitants

Country	Total Publications	Percentage Contribuitons (%)	SCP	MCP	MCP Ratio	Publications per 1M habitants
Singapore	910	1,3975	551	359	0,395	192,29
South Korea	5230	8,0316	4319	911	0,174	107,09
Sweden	442	0,6788	270	172	0,389	47,34
Switzerland	364	0,559	223	141	0,387	47,18
Israel	271	0,4162	130	141	0,52	38,96
Australia	796	1,2224	380	416	0,523	37,09
Canada	1095	1,6816	648	447	0,408	32,87
Germany	2602	3,9958	1974	628	0,241	31,82
Slovenia	56	0,0859	41	15	0,268	27,61
US	7734	11,8769	5928	1806	0,234	25,74
China	33138	50,8892	27795	5343	0,161	24,61
Ireland	105	0,1611	75	30	0,286	24,55
Japan	3059	4,6976	2670	389	0,127	23,98
Qatar	35	0,0537	18	17	0,486	22,64
Belgium	244	0,3744	146	98	0,402	22,58
Denmark	117	0,1795	62	55	0,47	21,25
Norway	100	0,1534	63	37	0,37	20,68
France	1216	1,8674	824	392	0,322	19,69
Austria	158	0,2425	96	62	0,392	18,8
Finland	95	0,1458	61	34	0,358	17,83
Uk	833	1,2792	481	352	0,423	13,35
Spain	545	0,8369	326	219	0,402	12,34
Netherlands	185	0,2839	326	219	0,402	11,26
Italy	581	0,8922	373	208	0,358	9,88
Portugal	93	0,1427	35	58	0,624	8,99
Bulgaria	68	0,1043	42	26	0,382	8,94
United Arab Emirates	51	0,0782	33	18	0,353	8,08
Estonia	11	0,0168	4	7	0,636	8,08
Poland	306	0,4699	241	65	0,212	7,99
Czech Republic	79	0,1212	35	44	0,557	7,55

Abbreviations: SCP, single country publication; MCP, multiple country publication

Table 3 illustrates countries contributions in terms of articles per million habitants. From this representation, the top ranked countries are slightly different from Table 2, with Singapore ranked in first and despite is size it is clearly a great contributor to LIBs knowledge production and dissemination. Small European countries like Sweden, Switzerland and Slovenia play an important role as well, outstanding in terms of contributions per million habitants. Other grater contributor is Israel ranked in fourth, once again demonstrating the power that small countries can have when it comes to contributions on Libs domain.

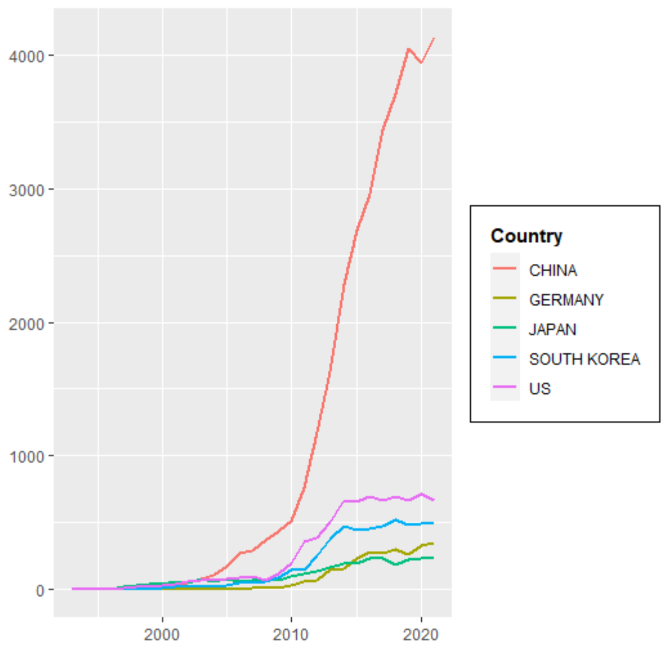
Figure 4 – Countries collaborations



Co-authorship can be seen as an indicator of the geographical/region distribution within a specific topic or domain, as it can show the scholars cooperation work patterns, local or global.

In Figure 4 the visual mapping of multiple countries collaborations is displayed showing the network between them. From this visual map, the countries can be divided in four majors groups: China and US (yellow), European countries and other countries linked to them are divided in two other groups (red and green) and a fourth group with countries from Asia, Oceania and Middle East (blue). From this representation it can be clearly seen that the most productive countries are China and US accounting their node size and the two countries have a strong collaborative work that is shown by the linking line between them. China also has a strong cooperative work with Australia, UK and Singapore, and US has collaborative works with South Korea and UK.

Figure 5 – Top 5 prolific countries by paper production



The top 5 prolific countries in terms of papers production are mapped in Figure 5. It demonstrates that in the early years of LIBs research US, Japan and South Korea played an important role as pioneers of knowledge production in this topic, while China only started later in the late 90's. Meanwhile, US, Japan and South Korea paper production per year continue with a rising pattern, they were drastically overtaken by China's explosive paper production growth since 2010. China increased the annual publications specially after the first years of the 21st century, which grants 33138 of papers in 2021. This shows the constant increasing of interest by scholars in producing scientific papers on LIBs in China.

Table 4 – Top 20 country collaborations

Rank	Country	Country2	Co-authorship
1	China	US	3087
2	China	Australia	1095
3	US	South Korea	698
4	China	Singapore	612
5	China	UK	541
6	China	Germany	515
7	China	Japan	472
8	China	Canada	430
9	China	South Korea	368
10	US	Canada	345
11	US	Germany	291
12	South Korea	India	244
13	US	UK	241
14	Japan	US	199
15	US	France	173
16	Japan	South Korea	152
17	France	Germany	141
18	China	Saudi Arabia	139
19	UK	Germany	137
20	US	India	131

Table 4 denotes previous findings when it comes about countries collaborations, with China and US having the strongest partnership with 3087 co-authorship papers. China leads the co-authorship network with 9 out of the 20 partnerships represented in Table 3, US is second ranked with 6 collaborative partnerships. Together, China and US have more than half of the collaborations (15) which denote the importance of these two countries in LIBs knowledge production.

4.3. Institutes Contribution

Table 5 illustrates the top 20 institutes with the greatest number of papers on LIBs. The top 5 most prolific institutes are from China, other countries like Singapore, Australia, South Korea, and US have prolific institutes represented but with relatively less publications than China. The most prolific institute is Tsinghua University with 1393 papers, followed by Central South University with 1204 publications, third-ranked University of Science and Technology of China with a total of 1172 papers.

China has 15 institutes on top 20 with the largest number of publications, what accounts for a total of 12775 publications for Chinese institutes what demonstrates the power of knowledge production that China has in this domain and how fundamental LIBs development is among Chinese researchers.

Table 5 - Top 20 institutes with greatest number of publications

Rank	Institute	Total Publications	Country
1	Tsinghua Univ	1393	China
2	Cent S Univ	1204	China
3	Univ Sci And Technol China	1172	China
4	Univ Chinese Acad Sci	999	China
5	Zhejiang Univ	989	China
6	Sch Mat Sci And Engn	872	China
7	Shanghai Jiao Tong Univ	824	China
8	Nanyang Technol Univ	781	Singapore
9	Fudan Univ	755	China
10	Xiamen Univ	725	China
11	Univ Wollongong	701	Australia
12	Shandong Univ	690	China
13	Seoul Natl Univ	686	South Korea
14	Tianjin Univ	681	China
15	Nankai Univ	658	China
16	Peking Univ	626	China
17	Hanyang Univ	621	South Korea
18	Jilin Univ	599	China
19	Inst Phys	588	China
20	Chem Sci And Engn Div	569	US

Table 6 - Top 20 institutes with greatest number of citations

Rank	Institute	Total Citations	Country
1	Nanyang Technol Univ	243	Singapore
2	Tsinghua Univ	209	China
3	Univ Sci And Technol China	209	China
4	Univ Wollongong	194	Australia
5	Natl Univ Singapore	190	Singapore
6	Stanford Univ	186	US
7	Univ Texas Austin	186	US
8	Inst Phys	182	China
9	Univ Calif Berkeley	179	US
10	Fudan Univ	177	China
11	Zhejiang Univ	177	China
12	Nankai Univ	174	China
13	Univ Maryland	170	US
14	Hanyang Univ	166	South Korea
15	Chem Sci And Engn Div	165	US
16	Cent S Univ	158	China
17	Sch Mat Sci And Engn	157	China
18	Peking Univ	151	China
19	Shandong Univ	150	China
20	Univ Chinese Acad Sci	149	China

Additionally, Table 6 describes the top 20 institutes with greatest citations per papers on LIBs. The most influential and cited institutes are from China, but the first-ranked institute is Nanyang Technology University from Singapore with a total of 243 citations, followed by Tsinghua University and University of Science and Technology of China with both having 209 total citations. University Wollongong although have a rank in the middle of the table of top 20 most productive institute, is ranked in fourth on Table 6, what demonstrates the influence and quality of papers published on LIBs domain by this institute.

Table 7 - Top 20 non-academic institutes with greatest number of publications

Rank	Institute	Total Publications	Country
1	Technoctr Renault	261	France
2	CNRS	229	France
3	Japan Sci And Technol Agcy	60	Japan
4	Australian Nucl Sci And Technol Org	48	Australia
5	Mcnair Technol Co Ltd	47	China
6	Bresser	45	Germany
7	Guangzhou Tinci Mat Technol Co Ltd	40	China
8	Res And Dev Grp	40	Australia
9	Shenzhen Capchem Technol Co Ltd	22	China
10	Chang Gung Mem Hosp	21	China
11	European Synchrotron Radiat Facil	20	France
12	Contemporary Amperex Technol Co Ltd	18	China
13	Fraunhofer Ikts Dresden	17	Germany
14	Ningde Amperex Technol Ltd	15	China
15	ICMCB	14	France
16	Guangdong Brunp Recycling Technol Co Ltd	13	China
17	Guangzhou Great Power Energy Technol Co Ltd	13	China
18	Citic Guoan Mengguli Power Sci And Technol Co Ltd	12	China
19	Yardney Tech Prod Inc	12	US
20	Hefei Guoxuan High Tech Power Energy Co Ltd	11	China

Table 7 illustrates LIBs knowledge production in terms of non-academic institutes, this table present some diversity when it comes to sector areas that these institutes operate, having vehicles manufacturing (France Technocentre Renault), some research centers (CNRS, Japan Science and Technology Agency, Australian Nuclear and Science Technology Organisation) and presence of batteries manufacture (Guangzhou Great Power Energy Technology Co Ltd, Citic Guoan Mengguli Power Science And Technology Co Ltd, Yardney Technical Products Inc).

Table 8 - Top 20 non-academic institutes with greatest number of citations

Rank	Institute	Total Citations	Country
1	Technoctr Renault	105	France
2	CNRS	93	France
3	Japan Sci And Technol Agcy	37	Japan
4	Bresser	34	Germany
5	Mcnair Technol Co Ltd	30	China
6	Shenzhen Capchem Technol Co Ltd	20	China
7	European Synchrotron Radiat Facil	19	France
8	Res And Dev Grp	19	Australia
9	Contemporary Amperex Technol Co Ltd	16	China
10	Chang Gung Mem Hosp	15	China
11	Fraunhofer Ikts Dresden	14	Germany
12	ICMCB	14	France
13	Guangzhou Great Power Energy Technol Co Ltd	12	China
14	Yardney Tech Prod Inc	12	US
15	Citic Guoan Mengguli Power Sci And Technol Co Ltd	10	China
16	Guangdong Brunp Recycling Technol Co Ltd	10	China
17	IFW	10	Germany
18	BMW Grp Technol	9	US
19	Covalent Associates Inc	9	US
20	Hefei Guoxuan High Tech Power Energy Co Ltd	9	China

The top 20 non-academic institutes in terms of citation are presented in Table 8 and the top 3 ranked institutes is equal to the top 3 most productive non-academic institutes. The most productive and influential non-academic institute is France Technocentre Renault, which is from one of the sectors that have the most interest on LIBs development, vehicles manufacturing. On past years, vehicles manufacturing companies have invested in development of hybrid or fully electronic vehicles and LIBs is the main battery source used. A lot of development by means of investigations and knowledge production has been done by private sector what helps to support LIBs knowledge dissemination.

4.4. Authors Contribution

From the results so far analyzed, LIBs are a growing field of study year by year which is consequence of continuous authors curiosity about this domain and the attention that this type of battery is gathering. The assembled 65154 articles are provided by a total of 60210 different authors. The authors collaboration analysis can identify the core leading knowledge providers and their social cooperation networks [23].

The authors productivity can be measured some how in terms of the total publications that they make in a specific topic and top 20 most prolific authors on LIBs in number of publications are listed in Table 9. From table 9 is clearly outstanding that the most productive authors are from a specific country, China. Between the top 20 authors, 12 are from China what suggests that Chinese scholars play an important and crucial role on LIBs knowledge production. From those 12 Chinese scholars, 8 are present on the top 10 prolific authors.

The most productive author is Martin Winter, who is a scholar from University of Munster with 58 papers published on LIBs domain, followed by Yitai Qian from University of Science and Technology of China with 43 articles published and Wei Shan Li from South China Normal University with 35 publications.

Table 9 – Top 20 authors with greatest number of research publications

Rank	Authors	Total Publications	Institute	Country
1	Winter M.	58	Univ Munster	Germany
2	Qian Y.	43	Univ Sci And Technol China	China
3	Li W.	35	S China Normal Univ	China
4	Shu J.	34	Ningbo Univ	China
5	Chen L.	34	Inst Phys	China
6	Wu F.	32	Sch Mat Sci And Engn	China
7	Passerini S.	31	Helmholtz Inst Ulm	Germany
8	He X.	30	Tsinghua Univ	China
9	Wei M.	29	Fuzhou Univ	China
10	Xia Y.	29	Fudan Univ	China
11	Amine K.	28	Chem Sci And Engn Div	US
12	Nowak S.	28	Univ Munster	Germany
13	Chen J.	28	Nankai Univ	China
14	Li H.	26	Inst Phys	China
15	Novák P.	26	Paul Scherrer Inst	Switzerland
16	Zhang S.	25	Beijing Univ Aeronaut And Astronaut	China
17	Scrosati B.	25	Univ Roma La Sapienza	Italy
18	Liu Z.	25	Univ Nottingham Ningbo China	China
19	Wang G.	25	Univ Technol Sydney	Australia
20	Tarascon J.M.	24	Univ Picardie	France

Table 10 - Top 20 authors with greatest number of citations

Rank	Author	Total Citations	Institute	Country
1	Lou X.W.	9967	Nanyang Technol Univ	Singapore
2	Poizot P.	7067	Univ Picardie	France
3	Cui Y.	6130	Stanford Univ	US
4	Wu H.B.	5087	Nanyang Technol Univ	Singapore
5	Wan L.J.	4676	Inst Chem	China
6	Goodenough J.B.	4021	Univ Texas Austin	US
7	Grey C.P.	3826	Univ Cambridge	UK
8	Tarascon J.M.	3774	Univ Picardie	France
9	Nitta N.	3689	Sch Mat Sci And Engn	US
10	Sun Y.	3626	Hanyang Univ	Singapore
11	Wang G.	3549	Univ Technol Sydney	Australia
12	Gu L.	3544	Inst Phys	China
13	Guo Y.G.	3492	Inst Chem	China
14	Aurbach D.	3409	Bar Ilan Univ	Israel
15	Liu H.K.	3310	Univ Wollongong	Australia
16	Slater Md.	3306	Chem Sci And Engn Div	US
17	Xie Y.	3224	Univ Sci And Technol China	China
18	Xin S.	3210	Univ Texas Austin	US
19	Winter M.	3181	Univ Munster	Germany
20	Li H.	3062	Inst Phys	China

Table 10 illustrates the top 20 authors in terms of total citation. From Table 9 the distributions of authors per country is more heterogenous than Table 9, which shows a more variety of authors of different origin country represented on top 20. US and China have half of the authors together with 5 scholars from each country. On the other hand, it shows that the top 20 most prolific authors in number of publications may not be necessary the ones with the highest amount of citation on papers published, as only 4 of the top 20 most productive authors from Table 9 are present in Table 10 for the most influential top authors on LIBs domain. The top influential author is Xiong Wen Lou with a total of 9967 citations and he is from Nanyang Technol University in Singapore, which is the most influential institute from the dataset.

4.5. Research terms and hotspot trends

The terms that are used in the titles, abstract and keywords of collected dataset, for co-word analysis examines the relationship between keywords, and has proved to be efficient in revealing and grasping the progress of new frontiers of science [37]. This analysis can yield useful insights about the hot topics and future research trends and is a provider of the roadmap history from a domain.

To have a visual map of co-occurrence network, VOSviewer software was applied into the originally papers keyword with the only transformation made regarding the terms duplication in the matter of variations for the same term.

The extracted terms are screened in Figure 6, with a total of 200 terms present in the co-occurrence network. The node size represents the occurrence frequency of a specific term, the link distance between the nodes represents their relationship, shorter the distance higher the relations between nodes.
The central node is occupied with the term “lithium ion battery”, around it there are general terms like “performance” and “batteries” what can be spotted as well a more specific term on LIBs like “electrode” which is part of LIBs materials used either as anode or cathode materials.

Figure 6 – Terms clusters of papers on LIBs

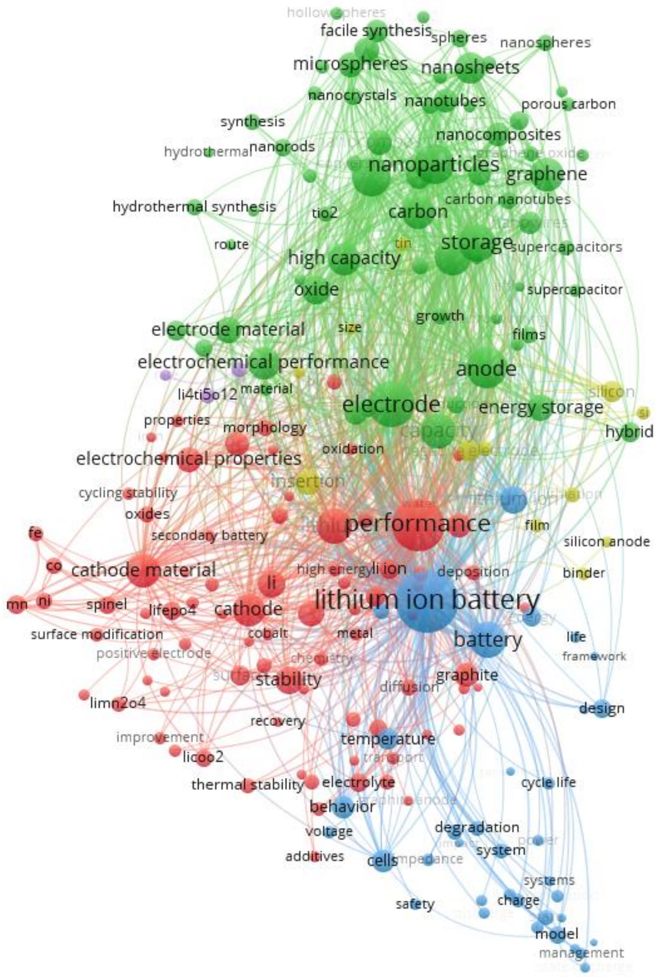


Table 11 – Terms with high frequency in clusters

Cluster	Label	High frequency terms	Cluster color	Cluster size
1	Performance and stability of LIBs positive electrode	Performance Cathode material Lithium Stability	(red)	82
2	Nanoparticles storage of LIBs negative electrode	Electrode Anode Nanoparticles Energy storage	(green)	67
3	Temperature management of LIBs	Lithium ion battery Battery Lithium ion Temperature	(blue)	36

The terms present in Figure 6 have 3 major clusters, denoted by cluster 1 (green), cluster 2 (red), cluster 3 (blue). The terms with the highest frequency within each cluster are illustrated in Table 11.

Three major clusters are grouped by the terms co-occurrence with the two main clusters, cluster 1 and cluster 2, respectively having the highest terms occurrence from all clusters. Analyzing the two major clusters, they are split into LIBs main materials components: the positive electrode (cathode) and the negative electrode (anode), which are directly related with the LIBs process in which progression of lithium ions from the cathode to anode and vice versa during charge/discharge process [38][39].

For the cluster 1 the most frequent term is “performance” which is directly related with the performance parameters, such as a high charge/discharge cyclability, a high energy density, a high rate performance, and a high safety of cells, is being strongly demanded. Many researchers and engineers are working to meet the needs of high-performance LIBs [17], followed by “cathode”, “lithium” and “stability”.

For cluster 2, the most frequent term is “electrode” and one of its key materials having high frequency, such as “anode” which is the negative electrode followed by “nanoparticles” term. Thus, terms including “energy storage”, “capacity” and “electrochemical performance” are also widely concerned.

Lastly for cluster 3, the term with high frequency is “lithium ion battery”, followed by “battery”, “lithium ion” and “temperature”. The terms in this clusters suggests the concerning about the battery heat processes has a whole as other terms such as “energy”, “behavior”, “cells” and “cycle life” can be spotted, which refers to LIBs charge/discharge process since LIBs is very sensitive to the heat and during this process it can over-heat if exposed to a certain temperature.

Table 12 – Evolution of top 30 Keywords used on LIBs research papers

Authors Keywords	Total	1993-1997 Publications	1998-2002 Publications	2003-2007 Publications	2008-2012 Publications	2013-2017 Publications	2018-2021 Publications
Lithium-Ion Batteries	1 (6750)	1 (48)	3 (90)	2 (225)	3 (578)	2 (2158)	1 (3651)
Lithium-Ion Battery	2 (6621)		1 (101)	1 (315)	1 (637)	1 (2254)	2 (3312)
Lithium Ion Battery	3 (3815)	9 (5)	2 (98)	3 (216)	2 (600)	3 (1734)	5 (1162)
Anode	4 (3552)		12 (30)	8 (119)	5 (406)	4 (1413)	3 (1584)
Lithium Ion Batteries	5 (2908)	6 (7)	4 (52)	5 (162)	4 (427)	5 (1174(	6 (1086)
Batteries	6 (2816)	24 (2)	14 (26)	10 (86)	10 (243)	6 (907)	4 (1552)
Li-Ion Battery	7 (2404)		7 (38)	4 (177)	6 (320)	7 (818)	7 (1050)
Li-Ion Batteries	8 (2115)		5 (59)	6 (133)	7 (295)	10 (673)	9 (964)
Battery	9 (1968)		10 (33)	11 (82)	11 (204)	9 (679)	8 (969)
Lithium-Ion	10 (1704)		11 (32)	23 (49)	15 (141)	13 (55)	10 (926)
Cathode	11 (1537)		15 (25)	9 (89)	8 (269)	11 (582)	13 (571)
Graphene	12 (1438)					8 (774)	15 (545)
Anode Material	13 (1397)		28 (13)	17 (59)	18 (132)	12 (581)	11 (612)
Cathode Material	14 (1309)		23 (19)	7 (120)	9 (248)	14 (544)	19 (378)
Lithium	15 (1290)	2 (17)	9 (37)	16 (60)	14 (174)	15 (508)	17 (494)
Electrochemical Performance	16 (1215)				21 (116)	16 (503)	14 (571)
Anode Materials	17 (1103)		25 (15)	24 (46)	23 (106)	18 (502)	16 (533)
Energy Storage	18 (1072)					17 (409)	12 (580)
Lithium Ion	19 (909)		27 (15)	22 (50)	19 (129)	19 (387)	21 (326)
Silicon	20 (908)				28 (88)	22 (369)	18 (415)
Cathode Materials	21 (884)	28 (2)		12 (79)	17 (134)	23 (351)	24 (306)
Electrochemistry	22 (840)				22 (113)	20 (379)	22 (325)
Electrochemical	23 (836)			25 (39)	16 (135)	24 (351)	25 (299)
Electrochemical Properties	24 (830)			13 (71)	13 (180)	21 (377)	
Lifepo4	25 (735)			20 (53)	12 (203)	28 (279)	
Carbon	26 (637)	3 (9)	17 (22)	30 (34)		29 (242)	
Electrolyte	27 (637)			18 (54)	30 (85)		29 (255)
Performance	28 (632)					30 (240)	23 (313)
Electrospinning	29 (625)					27 (290)	28 (259)
Nanoparticles	30 (599)					25 (307)	

The top 30 authors keywords in the study period are shown in Table 12. Terms like "lithium-ion batteries", "lithium-ion battery", "lithium ion battery", "lithium ion batteries", "li-ion battery" and "li-ion batteries", which refers to LIBs different terminologies, are the most frequent terms used in LIBs related articles. The main LIBs materials "anode" and "cathode" are a persistent focus topic in these energy store device research. In the early days of the study, carbon was used as a negative electrode, anode, and it was ranked in third in the period 1993-1997 being a clear hotspot topic, as carbonaceous materials have been widely used for the NE active materials of commercial LIBs [40].

As LIBs research evolved, new developments regarding the optimization of the LIBs components were made, and other source of materials being introduced to improve electrochemical processes, and new terms as "electrochemical performance", "electrochemical", "electrochemistry" and "electrochemical properties" begun to be new topic to explores. And from this constant search for evolution, new anode materials were introduced like "silicon", which display a focus topic having ascending ranks in Table 12. From other hand, with the introducing of this new source of negative electrode, "carbon" ranking decreased in the study period, while "graphene" become a new hot topic, as the most promising carbon based anode material [41].

From the positive electrode side, the introduction of "LiFePO4" is noted, with a rising number of articles using this term frequently. This introduction have been vital due to its low cost, abundance of mineral resources, safety, and so on [42]. In the latest years of this study, concerning with "energy storage" and "performance" related with LIBs are emergent topics and represent the continuous exploration for best performing combination between LIBs components.

4.6. Subject Categories

Table 13 illustrates the evolution of subject categories through study periods. The presented 8 subject categories were created based on the 24 research areas detected within the dataset extracted and transformed in a wider group.

Table 13 translates the total papers per categories in 6 different periods and is clearly outstanding that *Physical and Chemical Science* has been the leading category during all the study period followed by *Information technolog*y and these two categories are wide connected since the continuous research regarding the physical and chemical components of LIBs are seeking for the most recent technologies and methodologies to combine different materials to achieve better battery cycle life, capacity and low the costs of manufacturing. As LIBs is a very multidisciplinary area, other fields can be spotted in the ranking of publications as *Energy*, *Engineer and Computer Science* and *Metallurgy and Mining Processing*.

Table 13 – Subject categories evolution

Subject Categories	Total	1993-1997 Publications	1998-2002 Publications	2003-2007 Publications	2008-2012 Publications	2013-2017 Publications	2018-2021 Publications
Physical And Chemical Science	1 (55069)	1 (131)	1 (965)	1 (2511)	1 (6767)	1 (22500)	1 (22195)
Information Technology	2 (22100)	3 (24)	3 (164)	3 (495)	2 (1966)	2 (8478)	2 (10973)
Energy	3 (14926)	2 (70)	2 (336)	2 (741)	3 (1325)	3 (5565)	3 (6889)
Engineer And Computer Science	4 (5973)	4 (4)	5 (15)	5 (71)	5(339)	4 (1583)	4 (3961)
Metallurgy And Mining Processing	5 (3362)		4 (19)	4 (155)	4 (421)	5 (1079)	5 (1688)
Environment	6 (987)				6 (111)	6 (250)	6 (626)
Transportation	7 (286)			6 (1)	7 (19)	7 (82)	7 (184)
Health	8 (4)					8 (1)	8 (3)

In the last periods of analysis areas such as *Environment*, *Transportation* and *Health* have gained interest as field of research. As global concerns regarding climate changes and global warming are growing and gaining more visibility, research papers in *Environment* category is improving over time and it is expected that this rising pattern continue as new technologies continue to be explored to dimmish or overcome this social challenge of climate changes.

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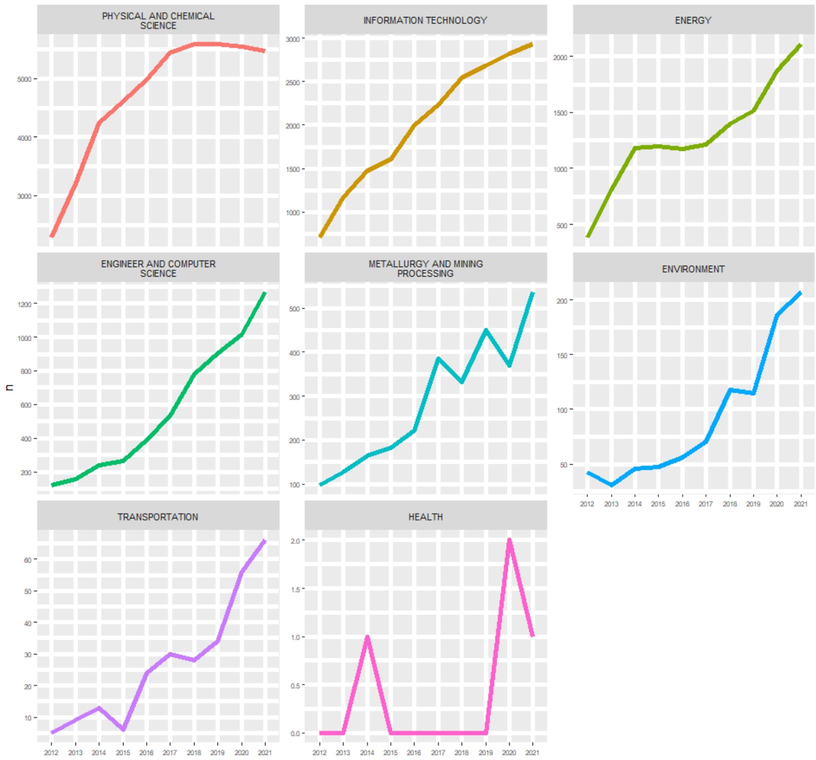
Figure 7 – Evolution subject categories



4.7. Journals Contribution

From statistical results, a total of 1320 journals published 65514 papers referring LIBs research. Table 14 summarizes the ranking evolution of top 10 most published journals on LIBs domain, which account 83% of the total publications output made in the study period. Journal of Power and Sources is the most prolific journal accounting with 6104 publishing papers, followed by Electrochimica Acta with 4348 articles and Journal of The Electrochemical Society with 2792 publications. These top 3 ranked journals have been a very active sources of LIBs papers dissemination since the early years of this study, having publishing articles e all the periods analyzed with a notable rising pattern.

Table 14 – Evolution of Top 10 most published journals

Journal	Total	1993-1997 Publications	1998-2002 Publications	2003-2007 Publications	2008-2012 Publications	2013-2017 Publications	2018-2021 Publications
Journal Of Power Sources	1 (6104)	1 (70)	1 (332)	1 (726)	1 (1131)	1 (2502)	1 (1343)
Electrochimica Acta	2 (4348)	4 (3)	4 (79)	3 (231)	2 (622)	2 (2155)	2 (1258)
Journal Of The Electrochemical Society	3 (2792)	2 (32)	2 (114)	2 (256)	3 (413)	6 (991)	5 (986)
Journal Of Materials Chemistry A	4 (2330)					3 (1608)	6 (772)
Acs Applied Materials And Interfaces	5 (2279)					5 (1108)	4 (1105)
Journal Of Alloys And Compounds	6 (2195)			10 (38)	7 (231)	7 (782)	3 (1139)
Rsc Advances	7 (1778)					4 (1375)	
Ionics	8 (1129)						8 (616)
Journal Of Physical Chemistry C	9 (1028)					8 (439)	
Solid State Ionics	10 (1009)	3 (16)	3 (93)	4 (135)	9 (161)		

Figure 8 – Top 10 most published journals 1993-2021

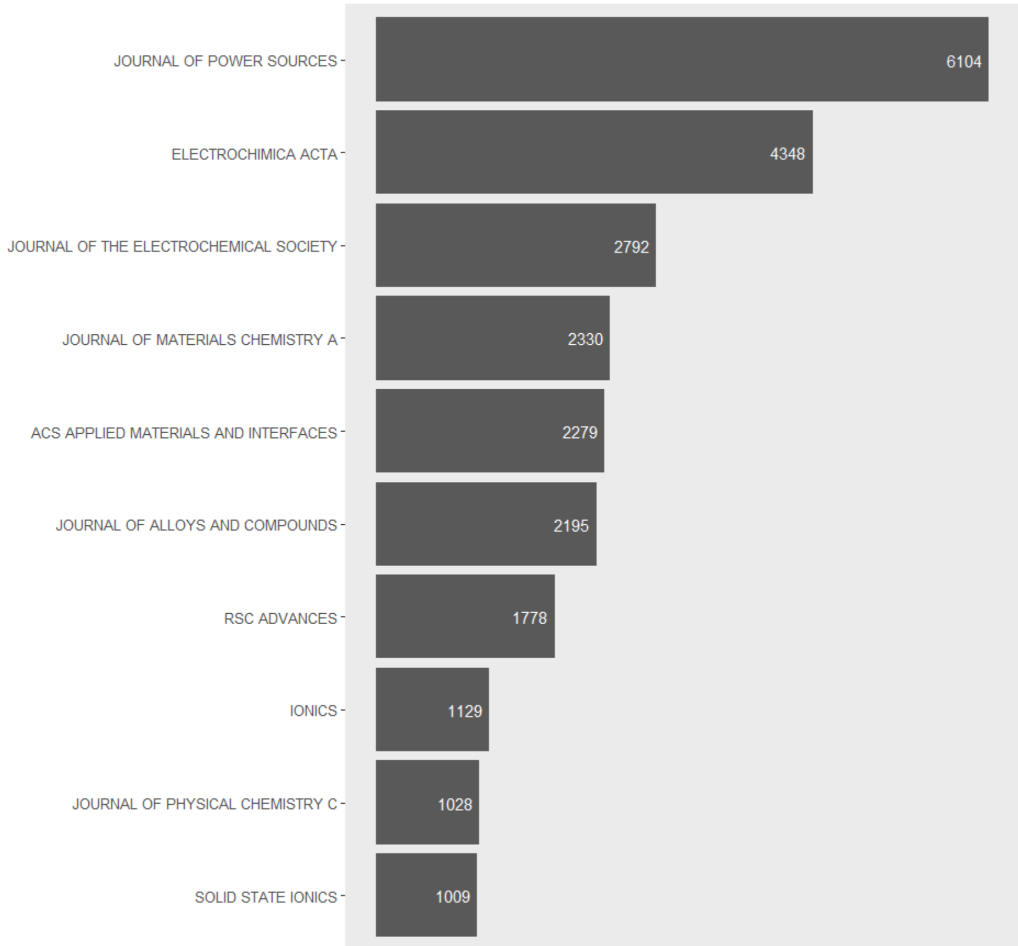


Table 15 – Top 10 most cited papers

Title	First Author	PY	TC	First Author Country	TA	TI	Journals
Nano-Sized Transition-Metaloxides As Negative-Electrode Materials For Lithium-Ion Batteries	Poizot P. Tarascon J.M.	2000	7067	France	5	1	Nature
Li-Ion Battery Materials: Present And Future	Nitta N.	2015	3689	China	4	2	Materials Today
Sodium-Ion Batteries	Slater M.D.	2013	3306	US	4	1	Advanced Functional Materials
Large Reversible Li Storage Of Graphene Nanosheet Families For Use In Rechargeable Lithium Ion Batteries	Yoo E.J.	2008	2448	Japan	5	1	Nano Letters
Graphene Anchored With Co3o4 Nanoparticles As Anode Of Lithium Ion Batteries With Enhanced Reversible Capacity And Cyclic Performance	Wu Z.S.	2010	2151	China	9	1	Acs Nano
Lithium - Air Battery: Promise And Challenges	Girishkumar G.	2010	2000	US	4	1	Journal Of Physical Chemistry Letters
Stable Cycling Of Double-Walled Silicon Nanotube Battery Anodes Through Solid-Electrolyte Interphase Control	Wu H.	2012	1963	US	11	2	Nature Nanotechnology
Lithium-Ion Batteries. A Look Into The Future	Scrosati B.	2011	1900	Italy	3	2	Energy and Environmental Science
Beyond Intercalation-Based Li-Ion Batteries: The State Of The Art AndChallenges Of Electrode Materials Reacting Through Conversion Reactions	Cabana J.	2010	1887	Fance	5	3	Advanced Materials
Nanostructured Materials For Electrochemical Energy Conversion And Storage Devices	Guo Y.G.	2008	1866	China	3	1	Advanced Materials

Abbreviations: PY, year published; TC, total citation; TA, total authors; TI, total institutes

The number of times a paper is cited in scientific journals, can be translate as a measure of it's influence and impacts in a specific field or domain, this indicator can be directly linked with authors influence and impact as well. Table 15 lists the top 10 most cited articles in the LIBs field in the study period.

These articles have a strong co-authorship, with none of them being a solely article and the first authors are from 6 different countries/region. More than half of articles are from only one institute, having multiple scholars participating in these articles, which demonstrates a high intra-organizational partnership among these institutes.

The most cited article is "Nano-Sized Transition-Metaloxides as Negative-Electrode Materials For Lithium-Ion Batteries" authored by Philippe Poizot, Stéphane Laruelle, Sylvie Grugeon, Loic Dupont and Jean Marie Tarascon and published in *Nature* journal, accounting 7067 total citations. All the scholars are from University of Picardie, France. Followed by "Li-Ion Battery Materials: Present And Future" by Naoki Nitta, Feixiang Wu, Jung Tae Lee and Gleb Yushin, published in *Materials Today* journal with 3689 citation.
The content of these articles is strongly linked with LIBs electrodes, positive and negative and their materials and the future challenges of these type of energy storage.

5. CONCLUSIONS

In this study, bibliometric methods were applied in global scientific production available on LIBs to assess, analyze and quantify and visualize the characteristics of knowledge production on this domain. In total 65154 records were obtained from WoS and were analyzed based on geographical distribution, institutions and authors publications, most frequent terms used, different subject categories and sources of dissemination. From the analysis, it shows that the first article related to LIBs can be traced back to 1993 and the cumulative number of papers increased, especially from 2010 onwards and this rising pattern still verified until now what demonstrates the level of attention that this domain is winning consecutively.

The LIBs domain is broadly international, with researchers from different countries/regions contributing with knowledge production and it can be summarized in three main geographical regions: Eastern Asia, North America, and Western Europe. The geographical analysis indicates that China and US are the two most prolific countries with 33318 and 7734 total publications, respectively, and the two countries have the strongest relationship in terms of collaborative works with 3087 partnership papers.
Concerning countries contribution in terms of research published per million habitants, small countries shows that their size are not an indicator of limitation when it comes to knowledge production, with Singapore ranked in first with 192,92 articles per million habitants and have the most influential institute and author. Others small countries as Sweden, Switzerland, Israel and Slovenia also make presence on top 10 countries demonstrating big impacts on LIBs domain.

Among the top 20 most productive authors, 12 are Chinese scholars and 2 of them are present on top 3 most productive authors. Martin Winter is the most prolific author having 58 publications, followed by Yitai Qian with 43 papers. China is the leader in absolute numbers when it comes with productivity with the largest number of total papers, institutions and authors publications but Chinese scholars and institutes in terms of influence are more limited based on the citations indicator. Consistent with this finding, China has the top 12 most productive authors but only one of these authors are ranked in the top 20 most influential authors and no Chinese author is ranked on the first 3 spots. Similar for Tsinghua University which is the most productive institute with 1393 published papers but is second ranked in terms of citation. On other hand, Nanyang Technology University which is eighth ranked in the top 20 most productive institutes, has the highest number of citation and Xiong Wen Lou, who is the most influential author is from this institute. Nanyang Technology University account 243 citations and Xiong Wen Lou 9967.

Non-academic institutes play an important role when it comes to contributions of LIBs output, since their knowledge production can accelerate the process of information dissemination and lower market prices with new technologies development and deployment. The most productive and influential non-academic institute is France Technocentre Renault, which is one of the leading automotive R&D center in Europe.

From the term analysis, it is possible to identify the evolution of the hotspot topics during the study period and since the early stage, research about electrode components (anode and cathode) are continuous topics of interest. Suggested by keywords analysis, new focus topics are arising in last years and they link with the electrochemical performance of LIBs components and the interactions between them. The emphasis of research hot topics keeps changing over time, what reflects on the rank and consequently, on the degree of importance and attention that topics have during the study distinct periods.

The subject category of Physical And Chemical Science has the most publications with 55069, Information Technology has 22100 and third ranked Energy with 14926. Another category that is spotted in recent years and is gaining more visibility, is Environment, this is consistent with the continuous awareness and concern that environmental issues are getting and outcome of the efforts in develop cleaner sources of energy.

The Journal of Power Sources has the largest number of LIBs publications accounting 6104 publications during the study period, second ranked Electrochimica Acta has 4348 published papers. Together with 8 remainder journals that compose the top 10 most published journals, they account 38% of total literature published. The most cited paper entitled "Nano-Sized Transition-Metaloxides as Negative-Electrode Materials For Lithium-Ion Batteries" authored by Philippe Poizot, Stéphane Laruelle, Sylvie Grugeon, Loic Dupont and Jean Marie Tarascon and published in Nature journal, has been cited 7067.

To summarize, this study provides an overview of the characteristics of research on LIBs. The research roadmap history, future research trends and challenges can be spotted along this paper different sections. The focus of this study was to extract meaningful information from the dataset retrieved using bibliometric analysis and visualizations tools to better understand LIBs trajectory and the main actors responsible for knowledge production and highlight future trends gathered from the analysis.

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