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The Evolutionary Dynamics of Battery Technology: A Knowledge-Based Assessment from Article Publications

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Dissertation

presented as partial requirement for obtaining the Master Degree Program in Data Science and Advanced Analytics

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THE EVOLUTIONARY DYNAMICS OF BATTERY TECHNOLOGY: A KNOWLEDGE-BASED ASSESSMENT FROM ARTICLE PUBLICATIONS

by

Eva Ferrer

Dissertation presented as partial requirement for obtaining the Master's degree in Data Science and Advanced Analytics, with a Specialization in Business Analytics

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration. I further declare that I have fully acknowledge the Rules of Conduct and Code of Honor from the NOVA Information Management School.

Eva Ferrer

Lisbon, 27th November 2023

DEDICATION

To my great-grandparents, Conceição Faria and Manuel Romano, for all the love, friendship, and life lessons they shared with me in the few years we had together. And for always showing me the importance of kindness and hard work.

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To my family and friends, for their support and words of encouragement, which gave me the motivation I needed to keep pushing forward.

And to Maxwell, for his everlasting friendship.

ABSTRACT

The energy storage research field has shown increased interest in technologies that can tackle the challenges brought on by lithium-ion batteries. However, there is limited information on what subjects are actually being studied, what publication trends look like and who are the scientific sponsors of those movements. This study relies on bibliometric and text mining approaches to analyze scientific publications on five emergent alternatives to lithium-ion, specifically, redox-flow, lead-acid, solid-state, lithium-sulfur and sodium-ion. The goal is to uncover publication trends between 2000 and 2021, identify what countries, authors and journals are contributing the most to this research, what topics are being investigated and discussed in each technology and to what extent these technologies are interrelated with the circular economy. There was an increase in the scientific outputs of all batteries throughout the time period, with China clearly leading the scene in terms of publication volume. The majority of authors and institutions publishing on redox-flow, solid-state, lithium-sulfur and sodium-ion were associated with Asian countries. On the other hand, lead-acid publications were mainly dominated by authors and affiliations associated with Europe. Most articles were either published on the *Journal of Power Sources* or on the *Journal of Materials Chemistry A*. The text mining analysis confirmed that rechargeable batteries have been growing in importance in the energy storage field. Circularity related publications have also increased, with most authors and affiliations being connected to the USA. All batteries, except solid-state, showed evidence of being highly related to circular economy approaches. Intrinsically, this study contributes to a thorough overview of the research framework on these technologies in the last two decades, while also shedding light on opportunities for further investigation, both from a scientific and circular economy standpoint.

KEYWORDS

Bibliometric analysis; Web of science; Secondary batteries; Circular economy; Text mining

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LIST OF ABBREVIATIONS AND ACRONYMS

WoS Web of Science

RFB Redox-Flow Battery

PbAc Lead-Acid Battery

SSB Solid-State Battery

Li-S Lithium-Sulfur Battery

NIB Sodium-Ion Battery

LIB Lithium-ion Battery

Li-ion Lithium-ion Battery

EV Electric Vehicle

1. INTRODUCTION

Rechargeable batteries have been around for over a century and since then they have played a crucial part in most of society's technological breakthroughs. The first practical rechargeable battery was invented in 1860 by the French physicist Gaston Planté (Kurzweil, 2010). It was built based on lead-acid chemistry and served as an important pilar for the development of other battery technologies as well as today's lead-acid battery (Kurzweil, 2010). However, almost two hundred years later, environmental concerns instigated by fossil fuel emissions and the consequent global warning have caused energetic priorities to shift towards solutions that can ease the impact of climate change through renewable energy integration and through the development of eco-friendly technology (e.g., Electric vehicles) (Ali et al., 2021).

The green energy revolution is dependent on cost-effective technologies that can provide sustainable energy storage. Much of that is related to the use of energy produced by renewable energy sources and to the integration of that same electricity in grid-scale energy systems. Secondary batteries are the most feasible technology to jump-start storage systems with renewable energy incorporation (Manthiram et al., 2022). The lithium-ion battery is currently one of the most well-known energy storage technologies and it is extensively used in multiple products, such as electronic devices and electric vehicles. However, one of the major drawbacks of this battery technology is the limited concentration of lithium resources in the Earth's crust which can lead to gradually increasing lithium prices (Kubota et al., 2018). Therefore, it is imperative to focus research attempts on alternative technologies that can tackle the challenge of scarcity and help shift the energy scene beyond lithium-ion (Chayambuka et al., 2020).

Nowadays, "post-lithium-ion" alternatives are extensively investigated and continue to spark interest from both an academic and industrial perspective (Placke et al., 2017). Research on substitute battery technology has been largely motivated by attempts at increasing energy density or at reducing costs, comparatively to lithium-ion. Other factors such as improved safety, cycle life and temperature are also considered (Nayak et al., 2018). An example of technologies that could replace LIBs are sodium-ion and lithium-sulfur batteries, largely due to their potential to be commercialized in the forthcoming years (Placke et al., 2017). Thus, this study centers its efforts on both these batteries, as well as additional technologies that could overcome lithium-ion's disadvantages. Specifically, the batteries under analysis are redox-flow, lead-acid, solid-state, lithium-sulfur and sodium-ion.

The purpose of this study is to make use of bibliometric analysis and text mining methods to inspect and analyze the academic production on the five proposed alternative technologies to lithium-ion, between 2000 and 2021. For each battery technology, the goal is to describe and characterize both the publication trends observed throughout the time period and the main scientific participants. Additionally, it looks to provide insights on what matters are being investigated in the energy storage field, both from a general knowledge perspective and from a specific circular economy perspective.

This study is structured as follows: Section 2 illustrates the battery technologies under study and the current literature on energy storage matters. Section 3 describes the methodology and data used for the analysis. Section 4 presents the results of the study which are then discussed and addressed in section 5. Sections 6 and 7 present the main conclusions and recommendations for future work, respectively.

2. LITERATURE REVIEW

2.1. BATTERIES

A battery can be described as unit for receiving, storing, and distributing energy when instructed to (Winter & Brodd, 2004). Theoretically, batteries are composed by two electrical terminals, a cathode (the positive electrode), and an anode (the negative electrode), which are them divided by a chemical compound named electrolyte (the ionic conductor) (Morris & Tosunoglu, 2012). In spite of being first developed as early as the 1800's, battery technology continues to be object of thorough investigation due to its intricate chemical composition and its potential to incentivize the current technological reality to a superior, more efficient performance. This study concentrates its efforts on secondary batteries, that can be discharged and recharged multiple times to provide or store electricity for a particular system, unlike primary batteries, which are single-use, discardable energy units.

Environmental concerns are ever-growing as the mass usage of fossil fuels, a limited, environmentally impactful form of energy, continues to overshadow the global energy demand (Martins et al., 2018). This has prompted the necessity of producing and gathering renewably sourced energy. Solar and wind have grown in popularity as renewable energy sources, however there are challenges associated with this type of energy. Electrical grids might need to resort to fossil fueled power plants whenever these sources are not available, to ensure a consistent energy supply. Electrical storage systems (EES) show potential to elevate energy systems to smart grids and enable renewable energy to be incorporated into power centers (Yang et al., 2011), thus permitting renewable sources to be as reliable as standard energy systems (Nair & Garimella, 2010). Yet it is critical to consider energy storage systems that provide fewer deployment costs, increased efficiency, and that continuously enable the application of renewable storage solutions (Muddasar et al., 2022).

Rechargeable batteries and other similar electrochemical energy sources reveal themselves to be strong candidates for positively affecting energy management and storing (Muddasar et al., 2022; Wu et al., 2017). This type of battery has been a leading energy technology for the past years due to its convenient characteristics, for instance high specific capacity, long cycle life and for its environmentally friendly impact (Luo et al., 2021). Currently the main commercial applications of rechargeable batteries are portable electronic devices, electric vehicles (EVs) and electrical storage systems (Goodenough & Kim, 2011). The focal task ahead is to develop safer rechargeable batteries for electric vehicles with higher driving range, improve the charging performance and lower the integration costs of electrical energy storage into the grid (Goodenough & Kim, 2011).

2.2. DIFFERENCE BETWEEN BATTERY TECHNOLOGIES

There is a broad variety of battery types that fall in the rechargeable battery spectrum, nonetheless, the analysis highlights a particular selection of relevant battery technologies that show potential to stand as an alternative for lithium-ion batteries and open the path for the fast-approaching era of post-lithium-ion batteries. Those are redox-flow (RFB) (da Silva Lima et al., 2021), lead-acid (PbAc) (Yanamandra et al., 2022), solid-state (SSB) (Kartini & Theresa Genardy, 2020), lithium-sulfur (Li-S) (Benveniste et al., 2018) and sodium-ion (NIB) (Chayambuka et al., 2020). For simplicity purposes rechargeable or secondary batteries will be referred to as *batteries* throughout the extent of this document.

Redox-flow battery is an unconventional rechargeable battery since its energy is stored in electrolytes rather than in electrodes as in standard batteries. RFBs are composed by redox couples that are stored in individual tanks and are connected to the energy-conversion cell stack through pumps. When the electrolytes are together in the battery stack, electrochemical reactions occur, and power is generated (Perry & Weber, 2016). RFB batteries make it possible for energy capacity and power generation to be independently determined. The capacity is associated to the volume of electrolytes kept in the battery system, the concentration of active species, the voltage of the cells and the quantity of stacks in the battery while power generation concerns the activity of the active species and the size of the electrode. This makes redox-flow batteries a scalable and flexible energy storage technology (Lourenssen et al., 2019). Other benefits include high endurance and efficiency, fast response-time, and low environmental impact, making this technology a robust candidate for supporting the integration of renewably sourced energy (Alotto et al., 2014).

Lead-acid batteries were invented in 1860, making them the first rechargeable battery to come to life. Since then, it has been object of fundamental investigation which led to the improvement of its development, design, and manufacturing, making it a leading electric power source with a relevant position in the energy storage field (Pavlov, 2011). They are comprised by a positive plate of lead dioxide, a negative plate of lead and an electrolyte that is a diluted sulfuric acid solution (Yanamandra et al., 2022). In addition to being a low-cost technology, lead-acid batteries are also fairly easy to manufacture and prove to have a good recharge efficiency (Jung et al., 2015). High recyclability makes this battery a sustainable option for tackling today's energetic requirements and circular economy objectives. Several studies by the Battery Council International reveal that between 2010 and 2019, lead-acid battery recycling increased from 95% to 99% (Yanamandra et al., 2022). Nevertheless, some of its underlying characteristics still pose a challenge for its application since generally lead-acid batteries have a low cycle life and energy density.[1] However, one of the main concerns lies in the chemical compounds used in its fabrication, given that arsenic and antimony, which are frequently included in alloys for lead-acid units, are threatening health hazards (Jung et al., 2015).

The development of solid-state batteries began as early as the 1800s, but its full potential was only uncovered later on, along with the creation of the first true all-solid-state battery. It is deemed as one of the main next-generation battery technologies, capable of fulfilling today's energetic requirements for an energy storage solution that is low-cost, safe and guarantees a high energy density and long cycle life (Nanda et al., 2018). All solid-state units use solid electrolytes to perform their energy charge and discharge and, inherently, that is the trait that makes them stand out as a viable option to overcome the safety concerns of batteries with liquid electrolytes, which is the case of the lithium-ion battery. A solid-state battery provides exceptional security since it has a less flammable electric system that can operate at a higher temperature and easily withstand shocks and vibrations (Kim et al., 2015). In addition to high safety levels, SSBs are also a sustainable alternative for providing energy to different applications. Leading companies like Toyota and BMW have shown interest in solid-state technology due to the developments on all-solid-state electrolytes. The former stated its

[1] The cycle life corresponds to the number of charge and discharge cycles a battery can achieve before its performance declines.

objective to launch electric vehicles powered by all solid batteries with sulfide-based solid electrolytes by 2022 (Ferrari et al., 2021).

Lithium-sulfur batteries have demonstrated the necessary characteristics to be considered a favorable secondary battery since their prototype was first released in the 1960s. Besides being a high energy density technology, this battery uses sulfur as its cathode. This material is one of the most abundant components on Earth, which makes lithium-sulfur batteries a low-cost option when compared to technologies that use expensive transition-metal compounds like cobalt. It is also an environmentally conscious alternative to other energy storage systems that use toxic transition-metal elements (Manthiram et al., 2013; Zhao et al., 2020). By combining metallic lithium and sulfur, the Li-S battery is able to generate nearly five times the high energy density produced by Li-ion units, at one-third of the cost, making it a potential substitute for lithium-ion batteries. However, there are still obstacles to the large-scale commercial application of lithium-sulfur batteries, such as low lifespan and a particularly complex sulfur electrochemistry. Additionally, the usage of dangerously reactive lithium metal can lead to safety concerns caused by internal short circuits, heat accumulation and the formation of gases (G. Li et al., 2018).

Sodium-ion batteries have been object of deep research in recent years for being a potential alternative for lithium-ion units. Besides both batteries having similar properties, one of the main components of NIBs, sodium, is the fourth most abundant elements on Earth with an extensive distribution across the globe. This reflects on the low-cost of sodium carbonate when compared to lithium carbonate and consequently on the pricing differences between both batteries (Hwang et al., 2017). Sodium-ion batteries demonstrate high adaptability since they are able to function even when internal or external heaters fail to maintain the battery temperature. From an ecological perspective, NIBs provide full-battery recyclability, which contributes to decreasing the need of primal resources by applying closed-loop recycling to electrode materials, and consequently translates to a positive environmental impact (Liu et al., 2019). However, this battery still faces a major challenge: discovering appropriate electrode materials that can compete with the performance provided by LIBs while also maintaining a low cost and providing effective sodium storage (Y. Li et al., 2017). Even though sodium-ion batteries are yet to surpass the current maximum energy density of lithium-ion, they are still strong candidates for stationary energy applications where energy density is not of the upmost priority (Peters et al., 2019).

2.3. BIBLIOMETRIC STUDIES ON BATTERY TECHNOLOGY

A number of article-based studies have emphasized the importance of analyzing trends and patterns found in research related to battery technology. This knowledge can contribute to the characterization of academic developments and to the identification of breakthroughs and focus areas as well as provide deeper insights on strategies for integrating sustainable energy technologies and new energy storage policies.

Zarate-Perez et al. (2022) proposed an analysis based on research articles related to lead-acid, redox-flow, lithium-ion, and other battery technologies to assess their individual performance and subsequent limitations for the integration of battery energy storage systems in microgrids. Cabeza et al. (2020) projected a study on different solutions for thermal battery management systems and employed a network analysis based on authors' keywords. It was found that lithium-ion and lead-acid are amongst the most frequent battery types identified through this exercise. W. Yang & Liu (2022) reviewed published literature on sodium-ion batteries and employed the term frequent-inverse text frequency (TF-IDF) algorithm, commonly applied in literature analysis, to identify the most relevant keywords related to the topic. The algorithm ignores high-frequency meaningless terms while keeping those that intrinsically translate the framework of the text. Liu et al. (2020) formulated a 12-year roadmap in sulfur cathode research and development for lithium-sulfur batteries, detailing the evolution of this component and providing new perceptions of what the future of the sulfur cathode can look like. It exposed major discoveries in sulfur cathode evolution throughout the years and identified the main contributions from countries, institutions, authors, journals, and others.

The present analysis looks to expand the current literature on battery technology by focusing its efforts on five potential battery technologies for the post-lithium-ion era and by considering a longer time span. The goal is to understand the research trends on each battery throughout the period under study and who are the main contributors for scientific production, thus contributing to a better characterization of the academic knowledge on these technologies. Specifically, the research gaps identified, and that the analysis aims to tackle are how article publications are distributed across the time period, what are the main countries publishing on the theme and what do their publication trends look like, who are the main contributors in terms of authors, affiliations and journals and what information can be obtained from articles' abstracts. This study differentiates itself by introducing a sustainability perspective into the analysis of these battery technologies. It provides a look into the evolution of publications related to sustainability and circular economy with the goal of identifying disruptive trends and understanding how these technologies position themselves as reliable options from a sustainability perspective.

3. MATERIALS AND METHODS

This analysis was conducted by means of a bibliometric analysis. Bibliometrics has been commonly applied as a technique for literature research. Since the century's early days, it serves as the foundation for literature statistics, scientific trend analysis and impact analysis across numerous fields (Lan et al., 2022). In accordance with Donthu et al., (2021), a bibliometric methodology includes the usage of quantitative and statistical evaluation techniques on data of bibliometric nature, such as academic publications, patents, or books. Its goal is to review, evaluate, and deliver a thorough understanding of the fundamental trends on research objects, for instance, authors, countries, journals, or institutions.

The research community has identified two main approaches for conducting a bibliometric investigation: *performance analysis* and *science mapping.* The first method aims to characterize how different scientific identities situate themselves in the field of study and to describe the scientific state of technology. The latter looks to produce a truthful representation of actual intellectual relationships between elements of a particular research field (Cobo et al., 2011).

Usually, *performance analysis* encompasses the use of one-dimensional or scalar methods which are focused on occurrence counts and other straightforward calculations. Depending on the subjects under analysis, one can illustrate the growth of a particular research field with annual-based publication data or identify the main authors, journals, or institutions through their contributions to the publication volume. Similarly, collecting keyword occurrences over time to perform content analysis can display prospective changing trends in the research of the studied topic. Applying this method makes it feasible to establish a bibliometric platform for monitoring and identifying the main characteristics, trends, and impact of the research area. *Science mapping* focuses its efforts on analytical, two-dimensional techniques that facilitate the identification and mapping of associations. Its findings are typically centered on co-occurrences, such as keywords that are frequently paired together, for example, N-grams. This approach facilitates the identification of scientific links and underlying relationships between elements under analysis (Gupta & Bhattacharya, 2004).

This analysis was supported by the use of *bibliometrix*, a powerful *R*-based library that facilitates the design of a comprehensive bibliometric and scientometric analysis (Moral-Muñoz et al., 2020). *Python* operated as a supporting tool for the production of plots and tables, with the purpose of showcasing the findings.

3.1. DATA COLLECTION

All the scientific publications were gathered from the Web of Science (WoS) Core Collection. WoS is a regularly used database for conducting bibliometric analysis. It is one of the largest, most reliable data sources for retrieving information about scientific articles and other publications of identical nature (Wang et al., 2023).

To initiate the data collection process, the following filtering criteria was applied to detect article publications associated to the five different battery types under analysis, between 2000 and 2021:

(TS=("redox flow") OR TS=("flow") OR TS=("redox") OR TS=("RFB") OR TS=("lead acid") OR TS=("lead-based") OR TS=("PbAc") OR TS=("solid state") OR TS=("SSB") OR TS=("all solid state") OR TS=("lithium sulfur") OR TS=("Li-S") OR TS=("sodium ion") OR TS=("NIB")) AND TS=(batter*)

All the keywords were included as topic terms (TS) so they could be detected in either the Title, Abstract, Author Keywords or in the unique WoS search field, Keywords Plus. The latter harvests the topic terms in the titles of cited articles to augment the reference searching power.

It is important to highlight that the search query includes the factual name of the battery types, alongside other allusive expressions such as acronyms or name variations, with the purpose of identifying as many related publications as possible. All these terms are brought together by the Boolean operator OR as to find publications associated to one or more of the forementioned batteries.

The Boolean operator AND was applied alongside a wildcard (batter*) to ensure that all articles include keywords analogous to battery-based terminology such as "battery" or "batteries".

The following step included pre-processing all the articles retrieved from WoS, with the support of R-software, eliminating the following:

- Publications from 2022 since the retrieval was conducted before the end of the year (1212 publications)
- Publications that were not articles (9947 publications)
- Publications that did not include the keywords of the initial search in the Title, Author Keywords or Abstract (960 publications)

The final dataset comprises a total of 46441 articles related to the battery types under analysis.

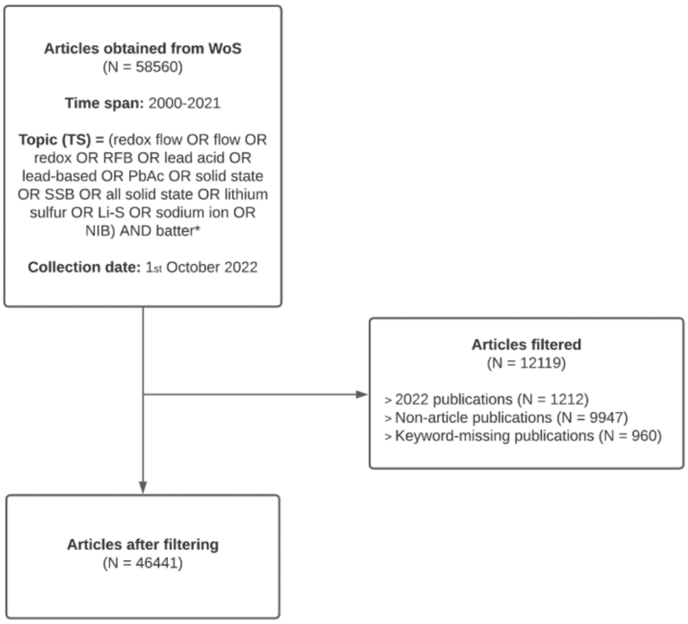

Figure 1 - Data collection diagram

4. RESULTS

In this section data is analyzed to showcase publication trends and characterize the elements participating in scientific progress by battery technology. Then the data is used to illustrate more specific insights regarding sustainability and circular economy. Below is the total number of publications per battery technology.

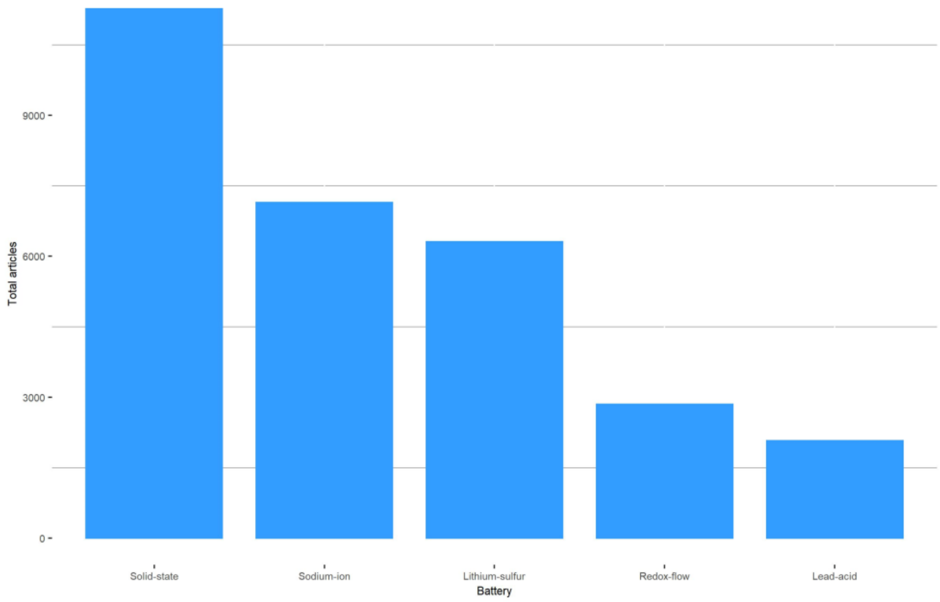

Figure 2 - Total publications per battery technology

4.1. SOME STYLIZED FACTS

4.1.1. The emerging trends of battery technology

The global yearly publication activity for redox-flow, solid-state, lithium-sulfur and sodium-ion related articles increased practically every year during the period under study. However, lead-acid related articles exhibit an irregular publication trend with accentuated increases and decreases throughout the timeframe. These dynamics are displayed in **Figure 3**, **Figure 4**, **Figure 5**, **Figure 6** and **Figure 7**.

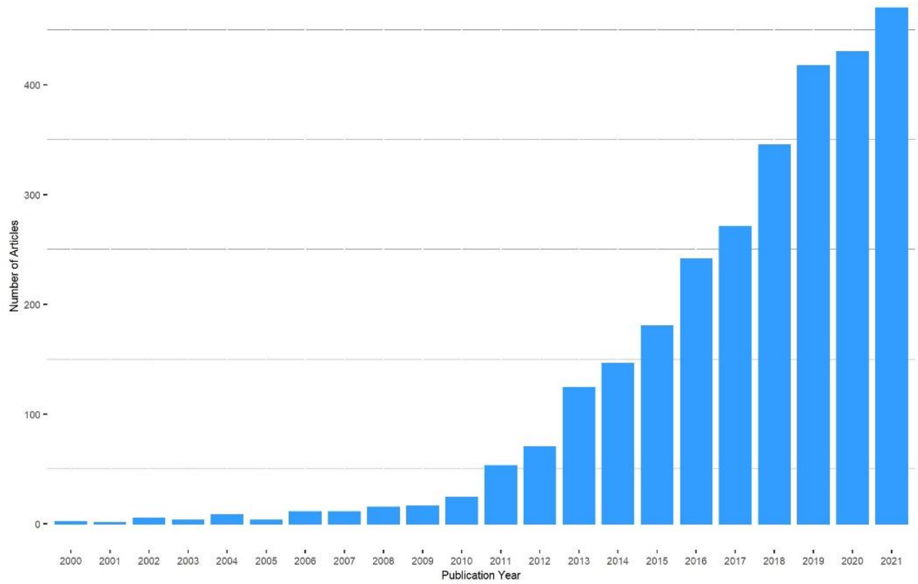

Figure 3 - Total number of redox-flow publications, 2000-2021

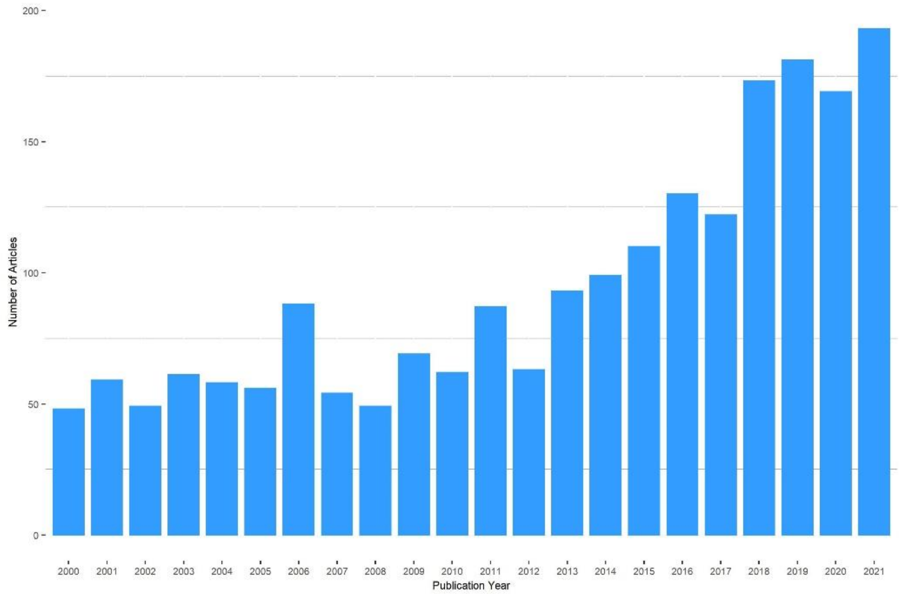

Figure 4 - Total number of lead-acid publications, 2000-2021

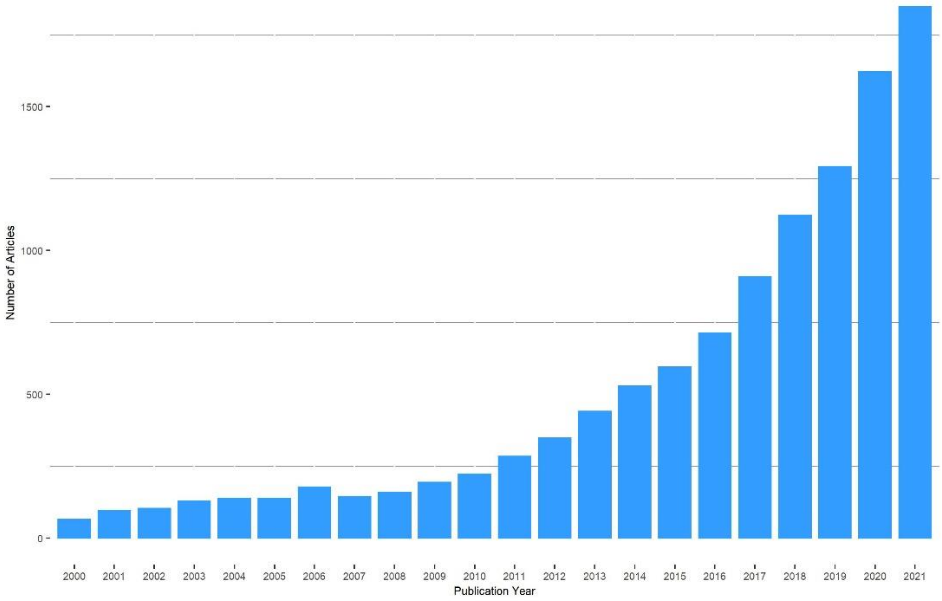

Figure 5 - Total number of solid-state publications, 2000-2021

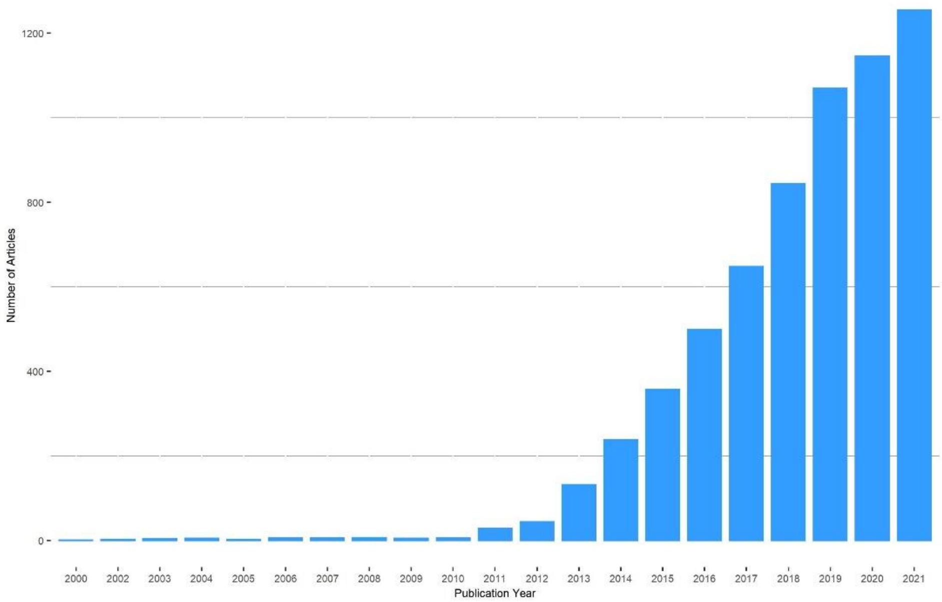

Figure 6 - Total number of lithium-sulfur publications, 2000-2021

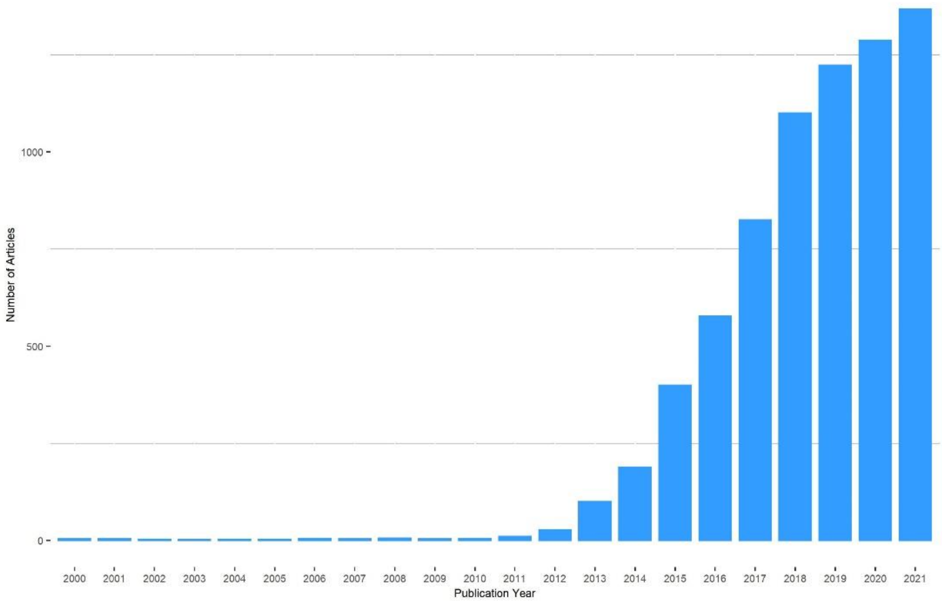

Figure 7 - Total number of sodium-ion publications, 2000-2021

4.1.2. The geographic contributors

Breaking down article publications by first author's country of affiliation, China clearly leads the publication scene for every battery technology, distancing itself the most from other countries in lithium-sulfur and sodium-ion research. **Figure 8** shows that publications related to redox-flow started to increase in 2009 with China and the USA displaying similar publication trends. By 2018 China had an accentuated increase in article volume, distancing itself from the other top countries. In contrast to other battery technologies, the publication of lead-acid related papers, presented in **Figure 9**, displays an irregular tendency. The USA was overtaken by China in 2005. India showed significant growth in 2020 and is now the second top country in terms of lead-acid publications. Article publications on solid-state, lithium-sulfur and sodium-ion had very similar trends. China registered a significant increase which started around 2015 and solidified its position as the leading country in terms of publication volume. The United States of America appears as the second top country for solid-state related publications. For lithium-sulfur and sodium-ion publications, South Korea and India are rising to this position, while the USA shows a slight decline in production volume. These facts are displayed in **Figure 10**, **Figure 11** and **Figure 12**.

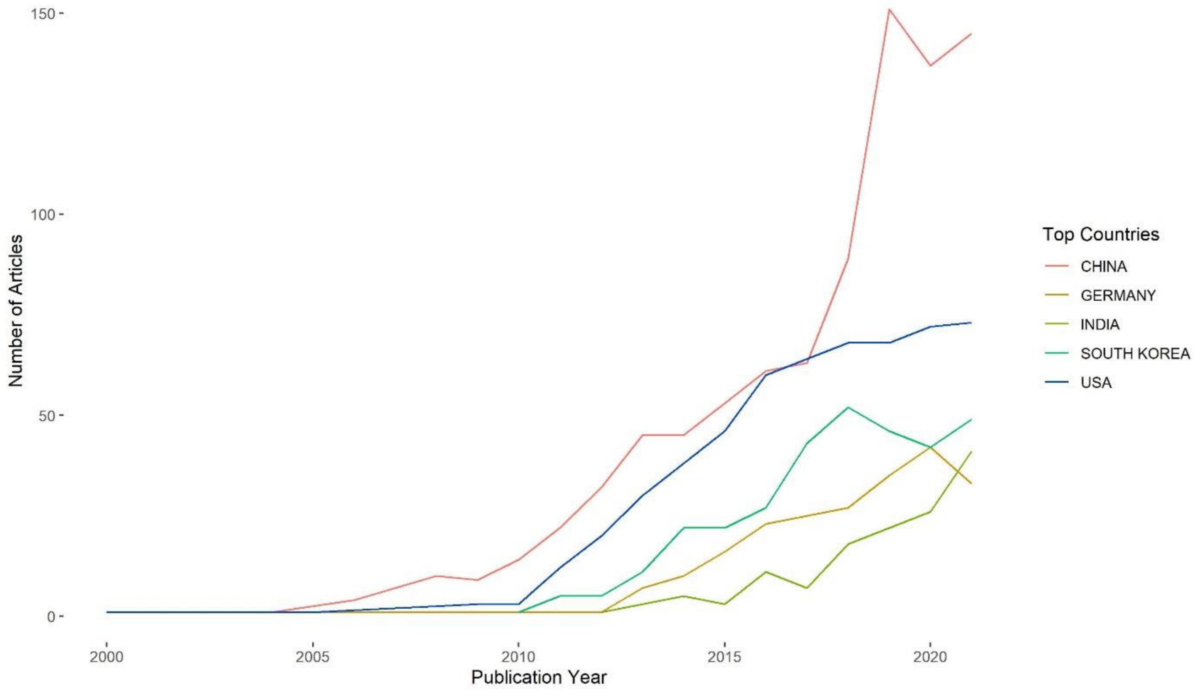

Figure 8 - Total redox-flow publications per first author's country of affiliation, 2000-2021

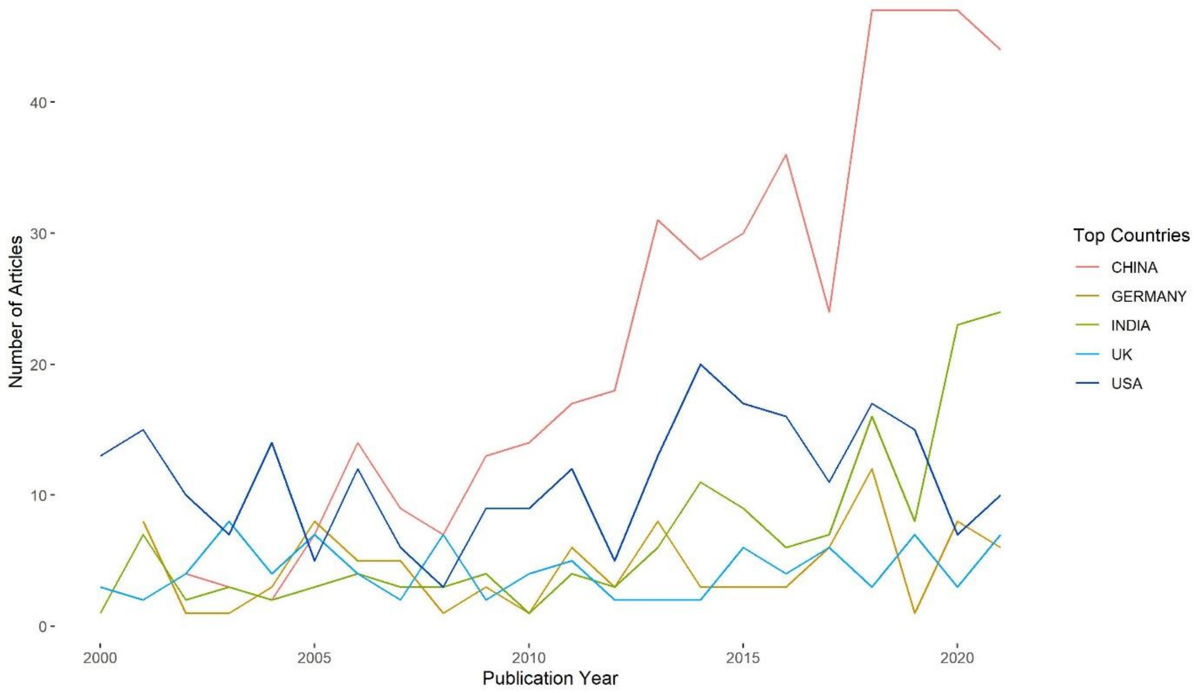

Figure 9 - Total lead-acid publications per first author's country of affiliation, 2000-2021

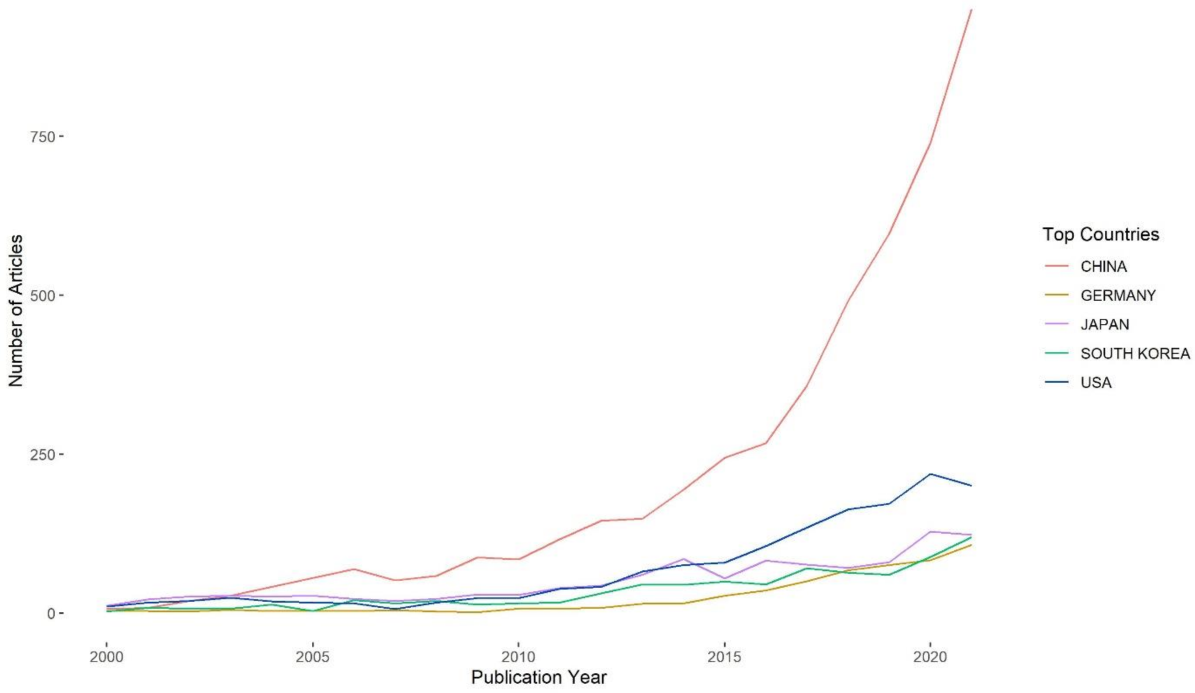

Figure 10 - Total solid-state publications per first author's country of affiliation, 2000-2021

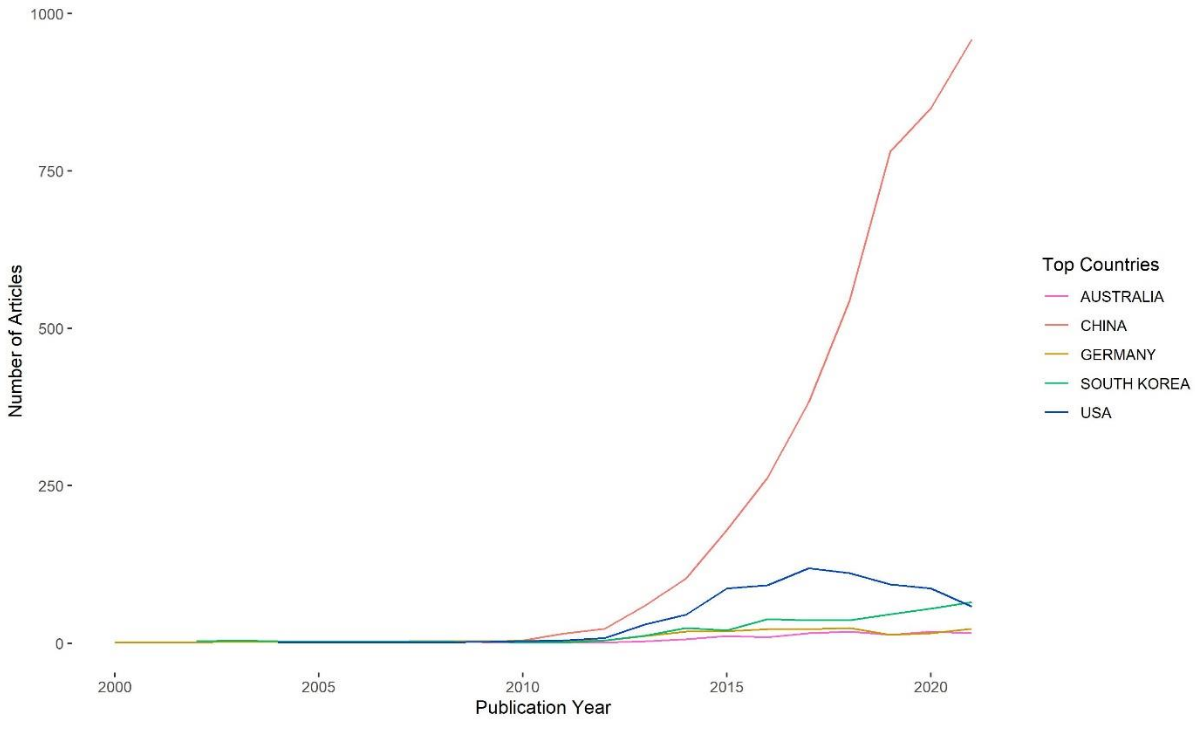

Figure 11 - Total lithium-sulfur publications per first author's country of affiliation, 2000-2021

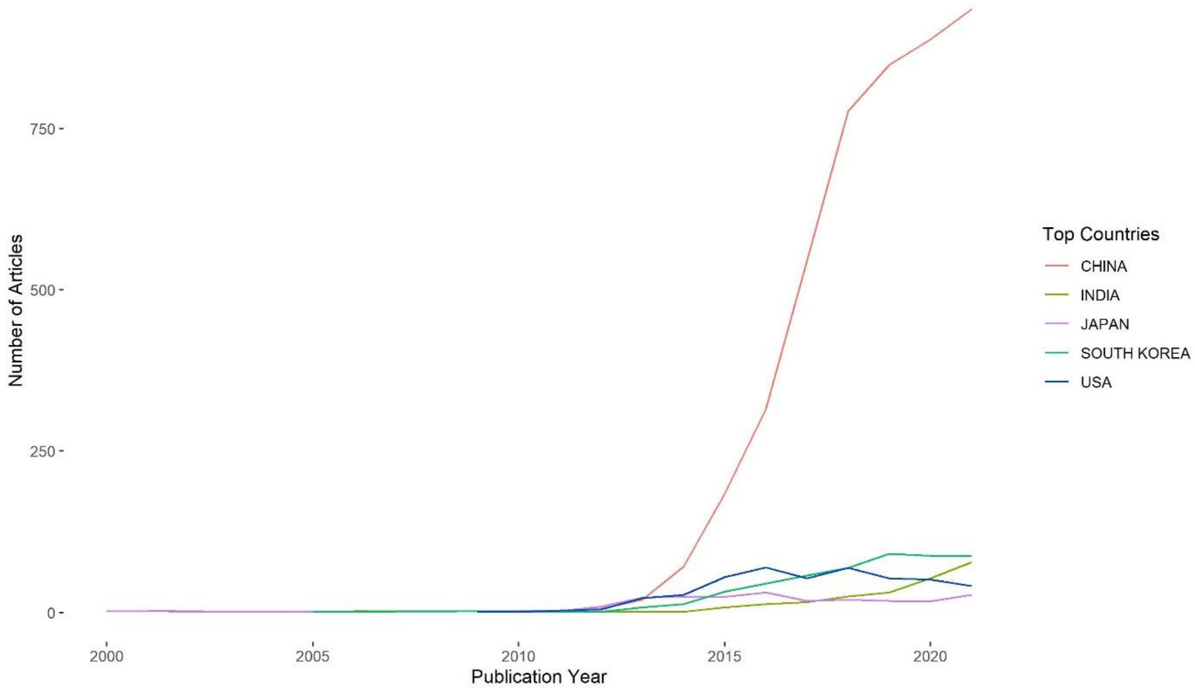

Figure 12 - Total sodium-ion publications per first author's country of affiliation, 2000-2021

4.1.3. International participation

The number of countries contributing towards the production of scientific outputs increased significantly for all battery technologies. Comparatively to what was seen before in **Figure 3**, **Figure 4**, **Figure 5**, **Figure 6** and **Figure 7**, the period in which the amount of contributors started to increase for each battery also corresponds to the period where the respective number of publications started to grow, specifically from 2010 onwards. In 2021, solid-state was the technology with the highest number of countries participating in related publications (63). It was followed by sodium-ion with 61 contributors and redox-flow and lead-acid with 51. Only 48 countries participated in lithium-sulfur related publications.

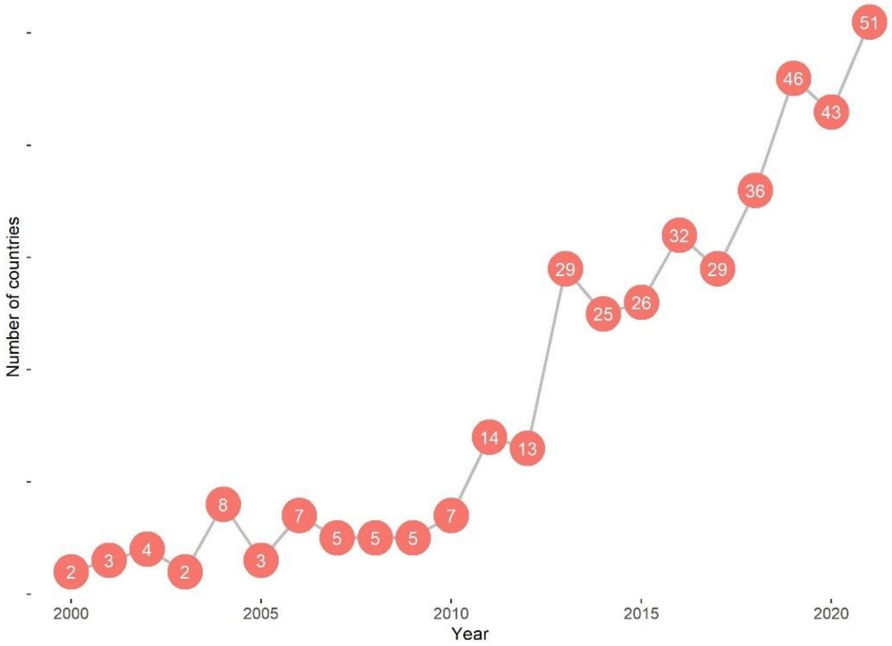

Figure 13 - Total unique countries participating in redox-flow publications, 2000-2021

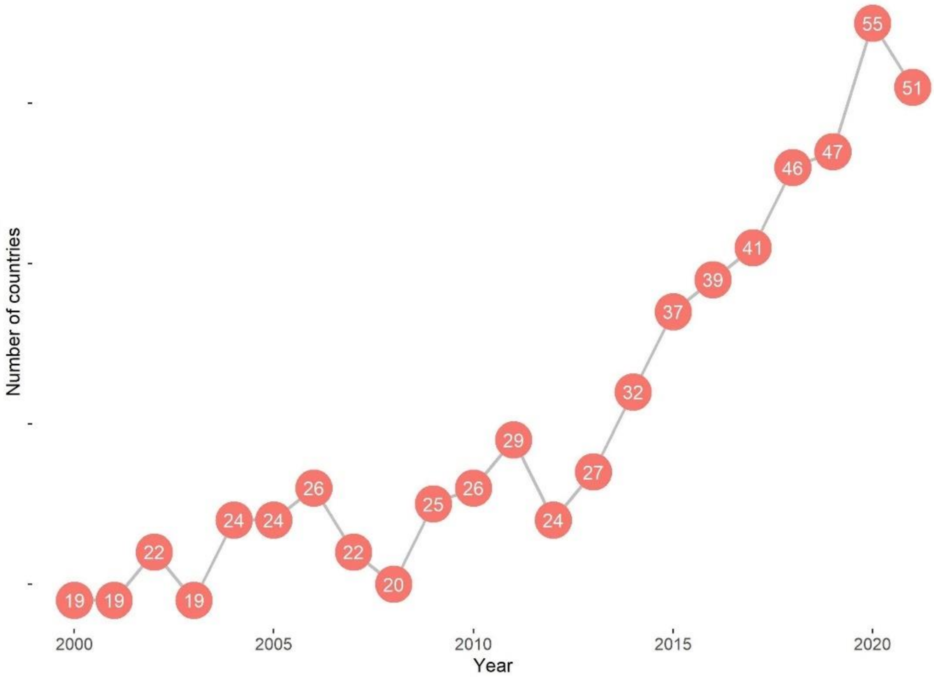

Figure 14 - Total unique countries participating in lead-acid publications, 2000-2021

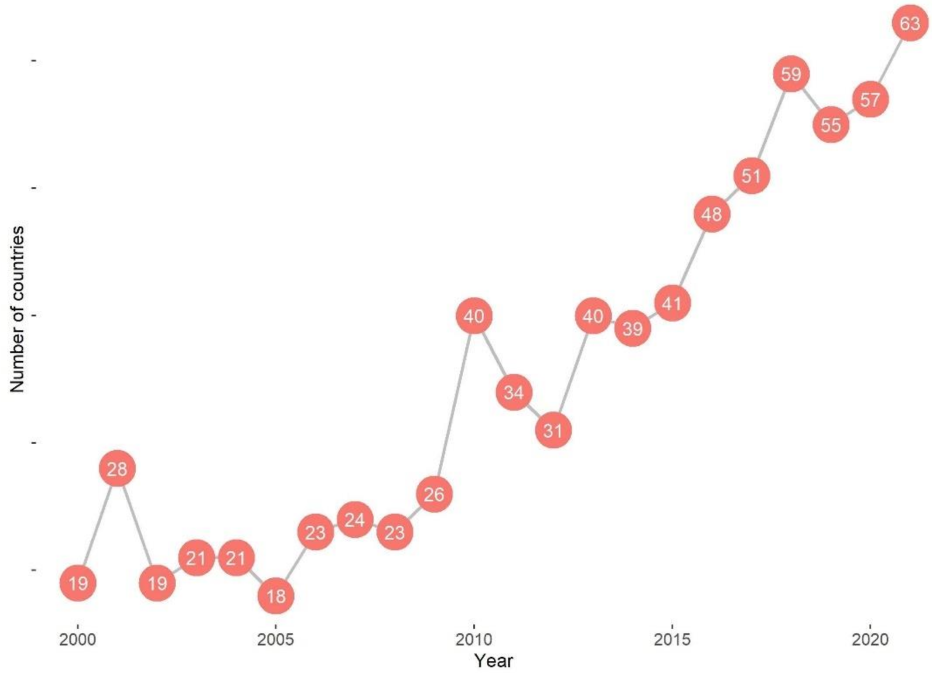

Figure 15 - Total unique countries participating in solid-state publications, 2000-2021

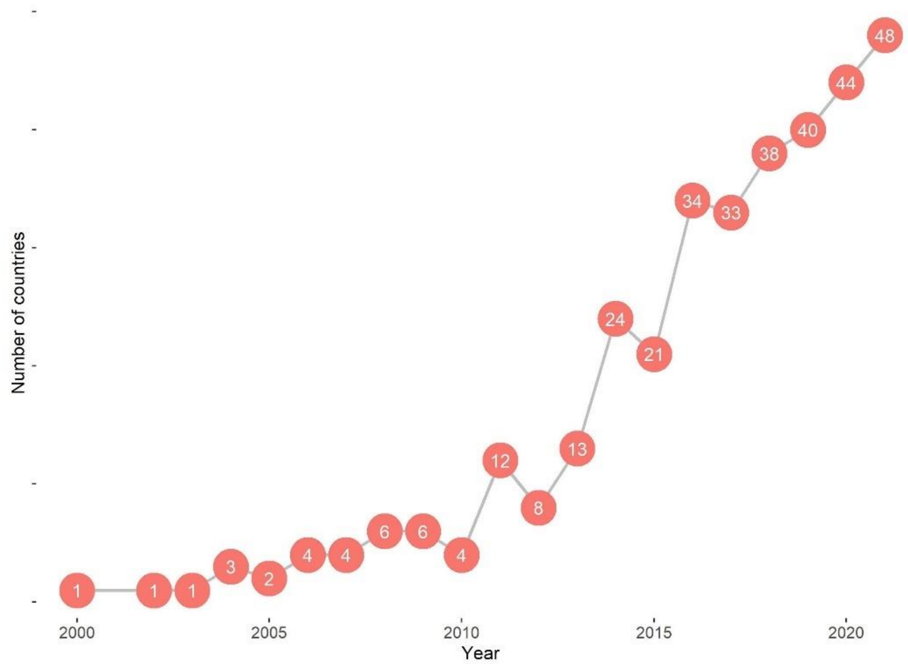

Figure 16 - Total unique countries participating in lithium-sulfur publications, 2000-2021

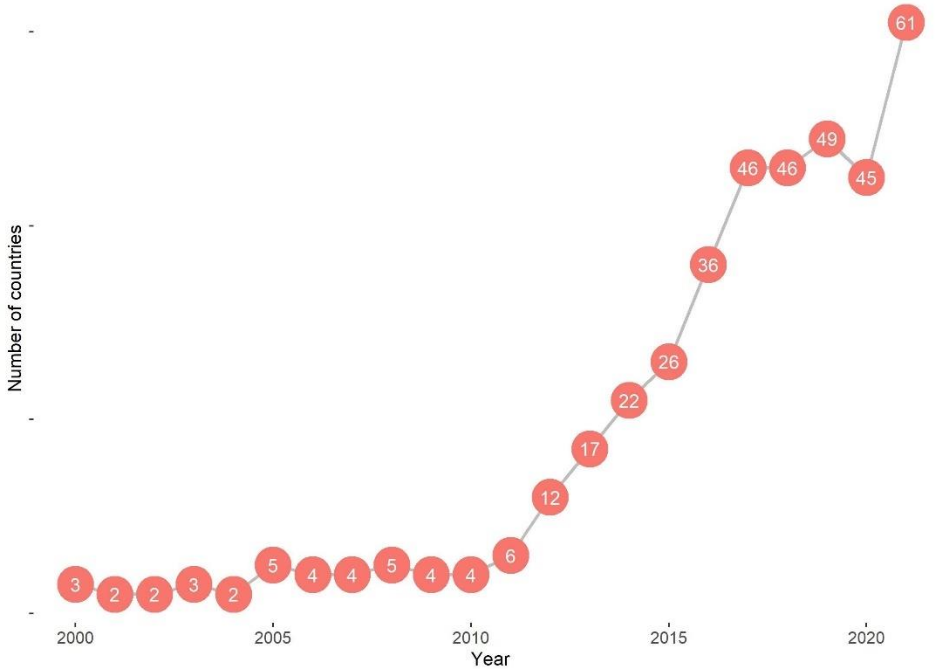

Figure 17 - Total unique countries participating in sodium-ion publications, 2000-2021

4.2. AUTHORS

Inspecting the top 20 publishing first authors by their continent of affiliation, it is clear that for all battery technologies, with the exception of lead-acid, most of the contributors are connected with Asia. **Figure 18** and **Figure 22** show that for redox-flow and sodium-ion, authors are geographically associated with Asia, Oceania, or the American continents. While Oceania and the Americas have the same authorship proportion in sodium-ion related publications, there is only one author linked to Oceania in redox-flow's top, which is associated to the University of New South Wales in Sydney. Additionally, it is relevant to mention that the top three authors in redox-flow publications are connected to Chinese institutions. Contrarily to other batteries, lead-acid publications are dominated by authors related to Europe, as seen in **Figure 19**. Additionally, the Americas are ahead of the Asian continent in terms of publications related to PbAc technology which also defies the conventional trends seen in other batteries' authorship. Analogously to redox-flow and sodium-ion, **Figure 20** highlights that authors of publications on solid-state are mainly associated with the Asian and American continents. There is a single occurrence of an author related to a European institution, the University of Giessen in Germany. It is important to highlight that for this battery, the top three authors are associated to the same institution: the Osaka Metropolitan University in Japan. **Figure 21** shows that the top authors in lithium-sulfur publications are either linked to the Asian or the American continents. Even though the majority of authors are connected to Asia, it is noted that the author with most publications on Li-S technology is associated to an American institution: the University of Texas at Austin.

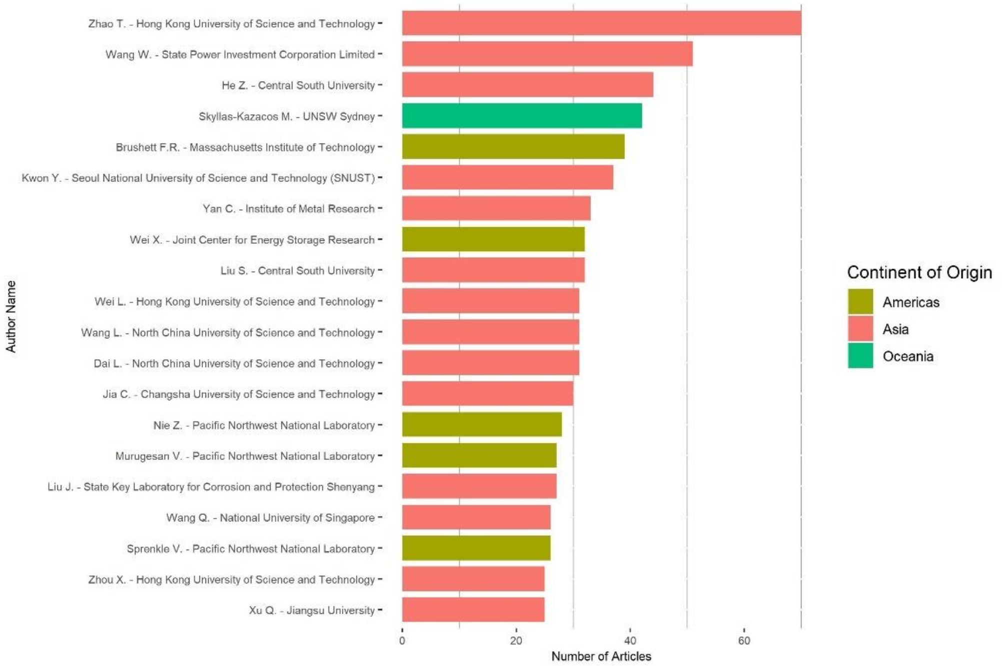

Figure 18 - Total redox-flow publications per author by continent of affiliation, 2000-2021

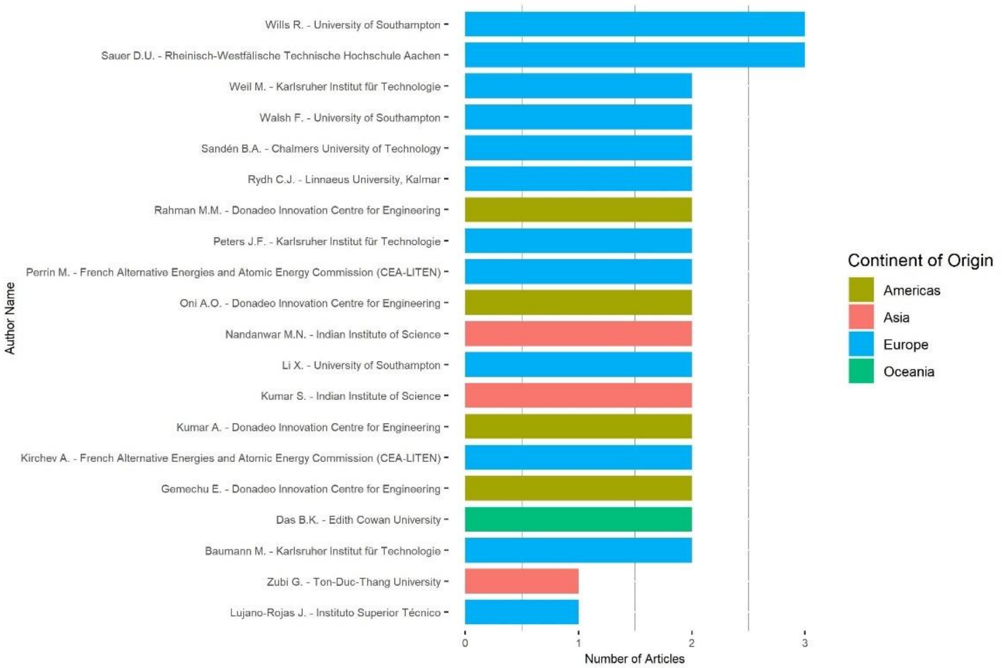

Figure 19 - Total lead-acid publications per author by continent of affiliation, 2000-2021

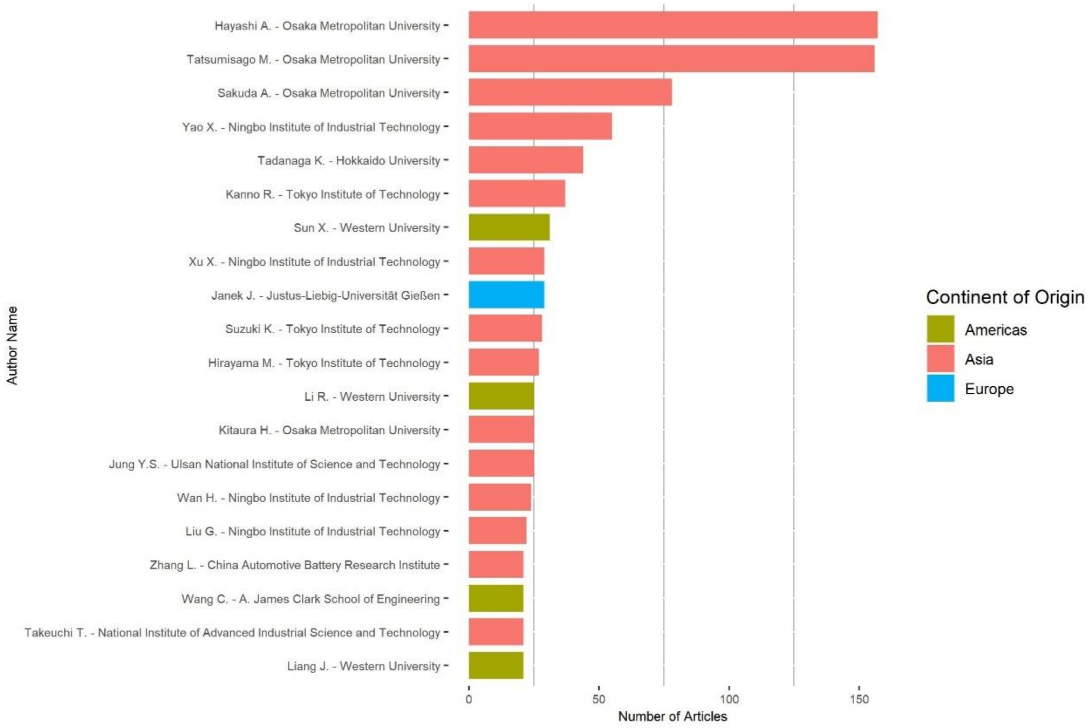

Figure 20 - Total solid-state publications per author by continent of affiliation, 2000-2021

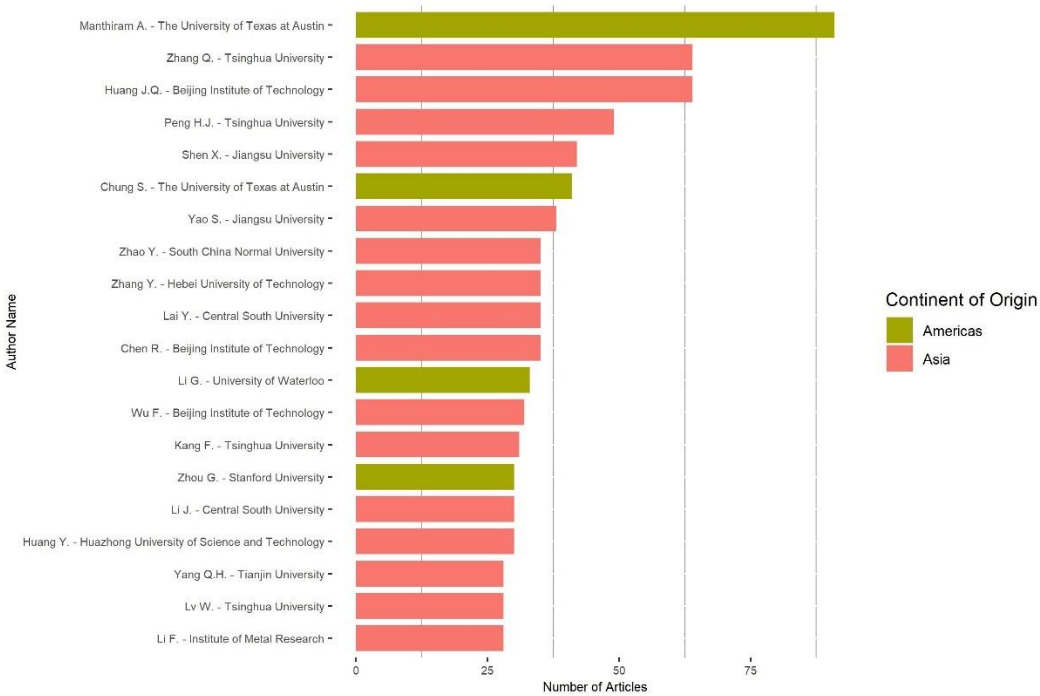

Figure 21 - Total lithium-sulfur publications per author by continent of affiliation, 2000-2021

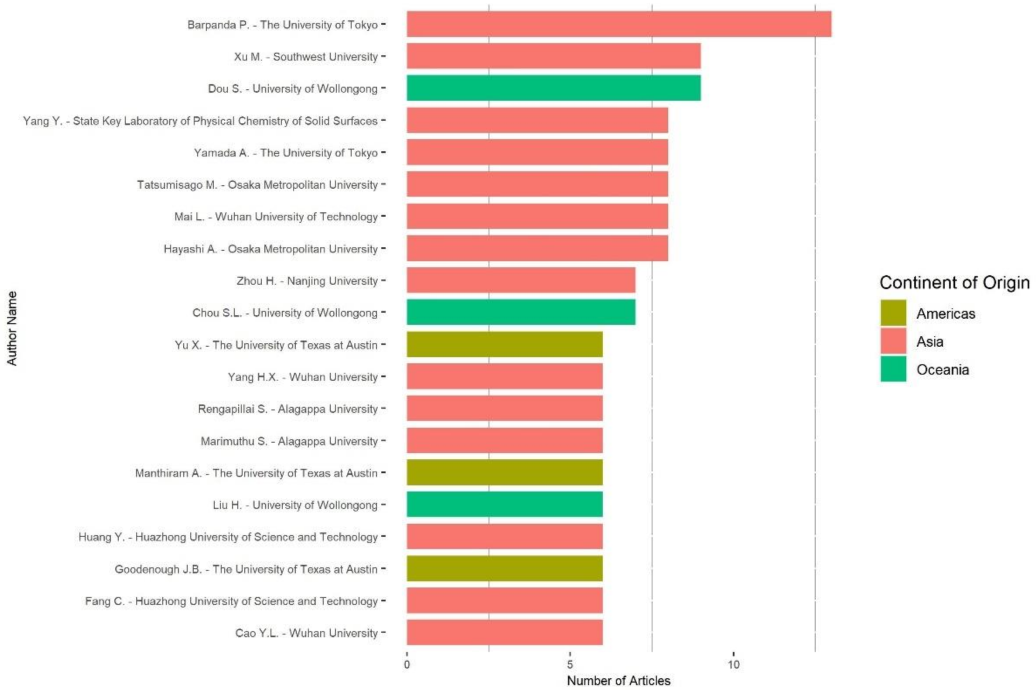

Figure 22 - Total sodium-ion publications per author by continent of affiliation, 2000-2021

4.3. AFFILIATIONS

Looking at the 20 institutions with most publications by country of origin, it is possible to conclude that the geographical distribution of the institutions is considerably diverse for all battery technologies, with the exception of lithium-sulfur. Additionally, for redox-flow, lead-acid and solid-state, the top institutions are associated to the top author of each respective technology (see **Figure 18**, **Figure 19** & **Figure 20**). **Figure 23** shows that Chinese and American institutions are the most prevalent in redox-flow publications, nevertheless, China detains the institution with most publications: the Hong Kong University of Science and Technology. **Figure 24** emphasizes that publications on lead-acid are dominated by European institutions. The top institution is the University of Southampton, located in the United Kingdom. There is also a considerable number of Asian universities amongst lead-acid's top. However, due to the low number of articles in this top, the results for this battery should be assessed in accordance. Solid-state publications are led by Japanese and Chinese institutions, as depicted in **Figure 25**. The top institution is the Japanese Osaka Metropolitan University. This reiterates the predominant role of this institution in solid-state research, confirmed before by the results depicted in **Figure 20**. There are only two European institutions amongst the most relevant affiliations, both based in Germany. Analogously, American institutions have the same proportion of appearance. It is important to note that the Toyota Motor Corporation is amongst the top affiliations publishing on solid-state. **Figure 26** shows that lithium-sulfur publications are completely dominated by Chinese institutions, with the top one being Tsinghua University. There is a single American affiliation publishing on this technology, the University of Texas at Austin. For sodium-ion publications, **Figure 27** exhibits that most institutions are Chinese, however the number one affiliation is the University of Wollongong, based in Australia. There are two German and American institutions in this top, still the number of articles published by the latter is moderately higher.

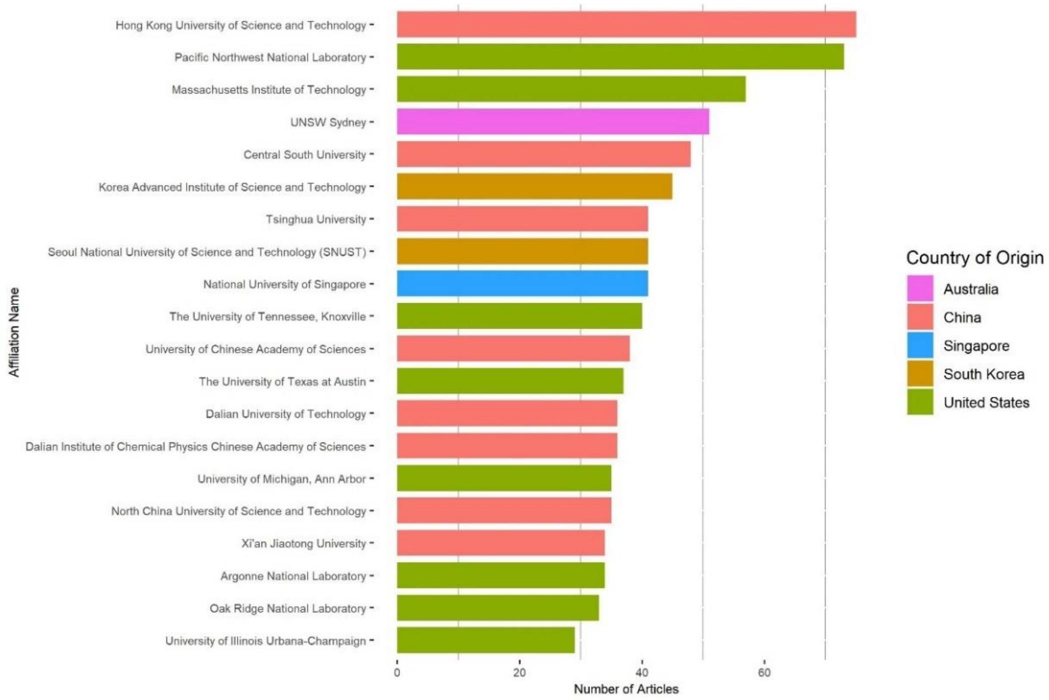

Figure 23 - Total redox-flow publications per affiliation by country of origin, 2000-2021

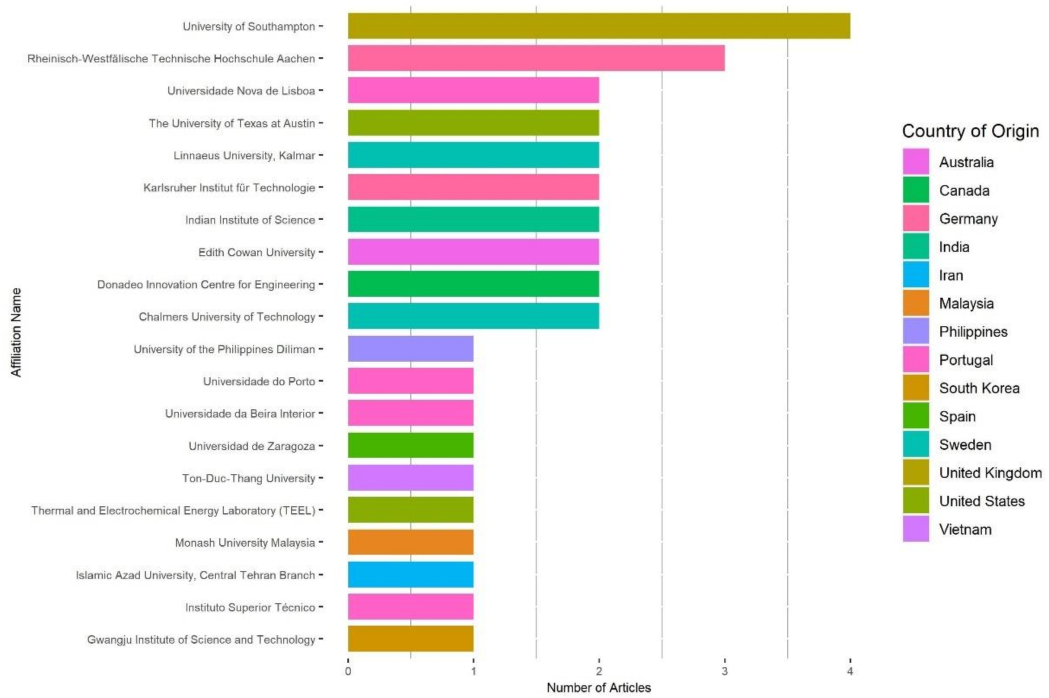

Figure 24 - Total lead-acid publications per affiliation by country of origin, 2000-2021

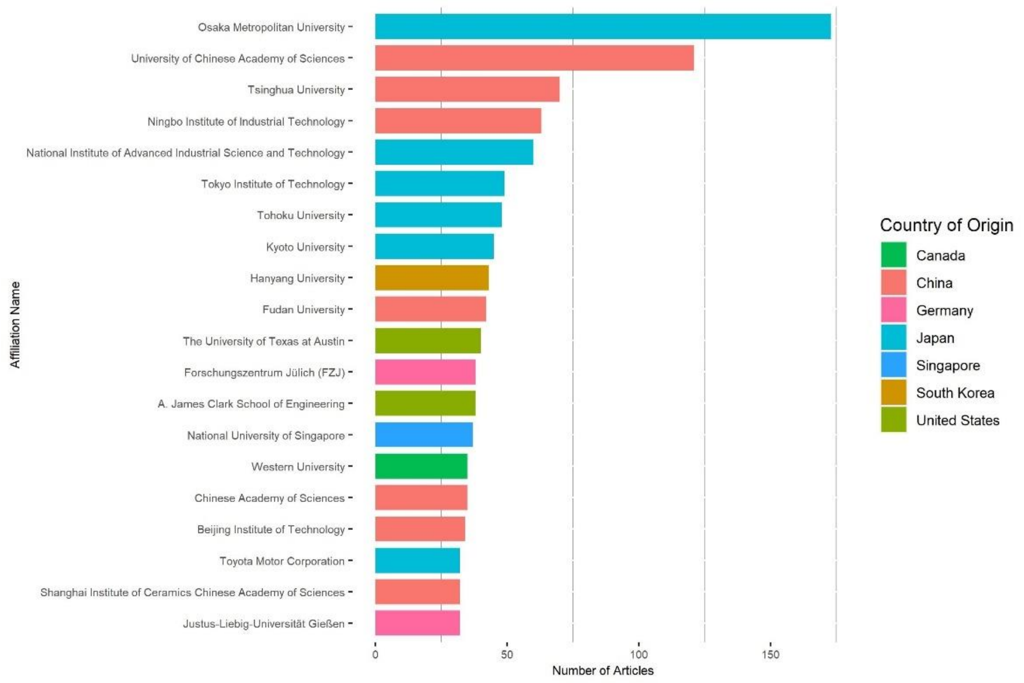

Figure 25 - Total solid-state publications per affiliation by country of origin, 2000-2021

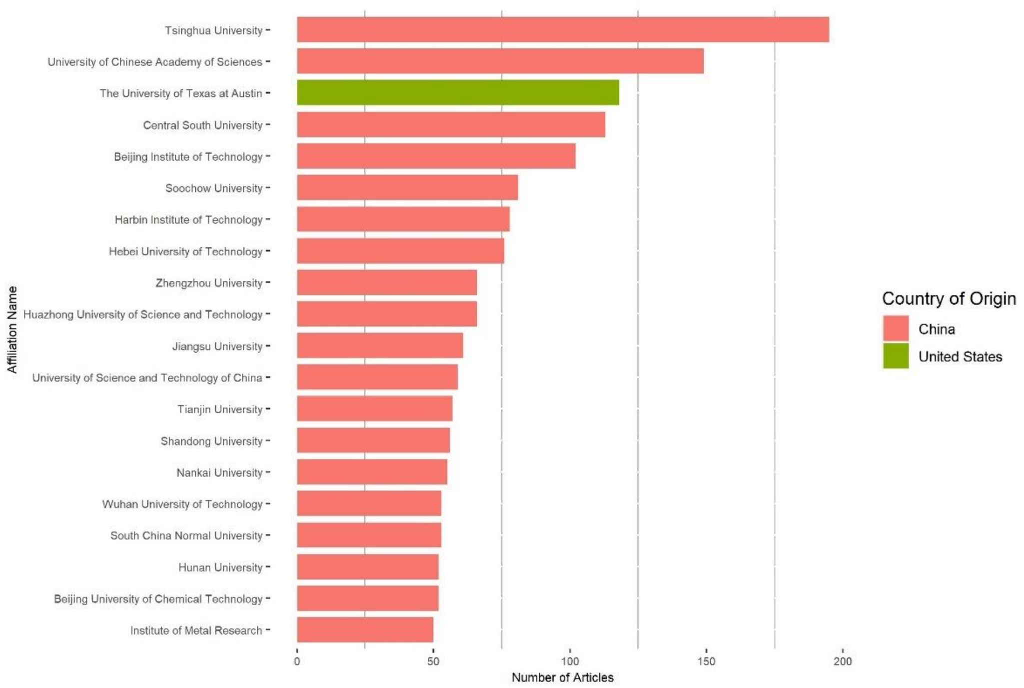

Figure 26 - Total lithium-sulfur publications per affiliation by country of origin, 2000-2021

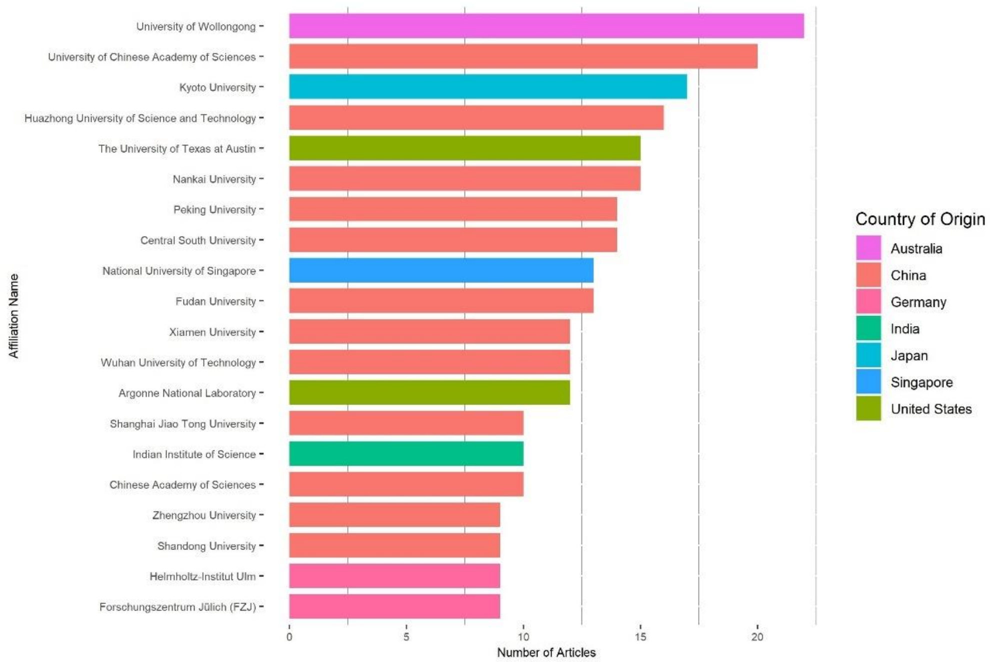

Figure 27 - Total sodium-ion publications per affiliation by country of origin, 2000-2021

4.4. JOURNALS

The scientific publications related to the battery technologies under study are predominantly published by the *Journal of Power Sources* and by the *Journal of Materials Chemistry A.* Furthermore, the vast majority of journals publishing on these batteries is directly related to the fields of energy, electrochemistry, materials, and electronics. According to the information displayed in **Figure 28**, **Figure 29** and **Figure 30**, the *Journal of Power Sources* is, by far, the number one publisher of scientific articles concerning redox-flow, lead-acid and solid-state batteries. Other relevant journals are the *Journal of the Electrochemical Society*, *Electrochimica Acta* and the *Journal of Energy Storage*, indicating that the research on these technologies is more focused on electrochemistry and energy storage matters. It is important to note that lead-acid publications are associated with two journals directly related to renewable energies and sustainability: the *Solar Energy* and the *Renewable Energy* journals (see **Figure 29**). The top scientific journal publishing on lithium-sulfur and sodium-ion technologies is the *Journal of Materials Chemistry A,* as seen in **Figure 31** and **Figure 32**. In fact, the four main publishers on these batteries are the same, with *ACS Applied Materials & Interfaces*, *Electrochimica Acta* and the *Journal of Power Sources* following the number one journal. This indicates that there is a considerable commitment to research focused on materials and electrochemistry topics related to these technologies.

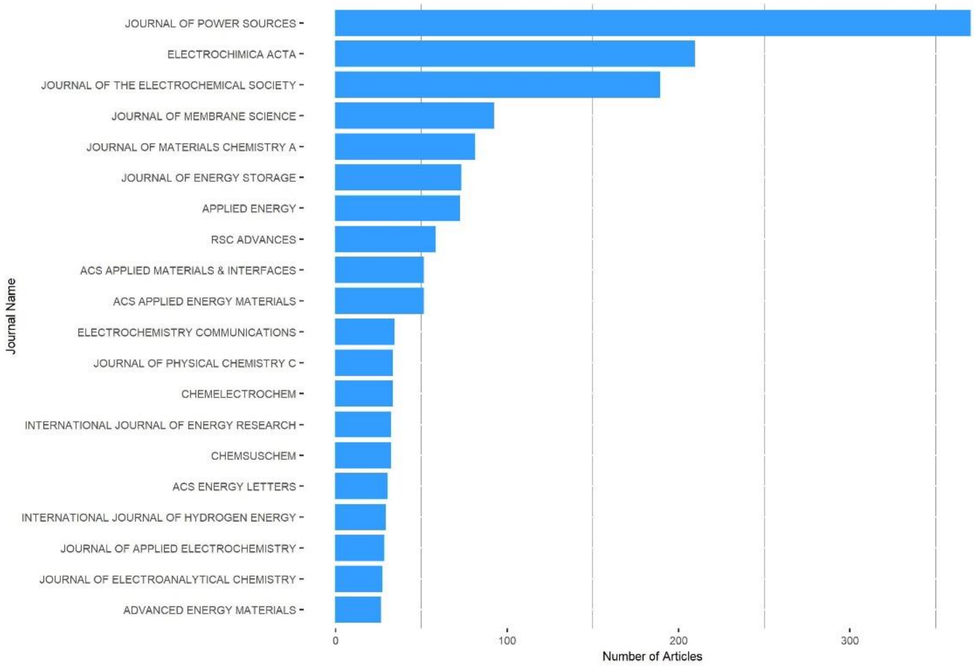

Figure 28 - Total redox-flow publications per scientific journal, 2000-2021

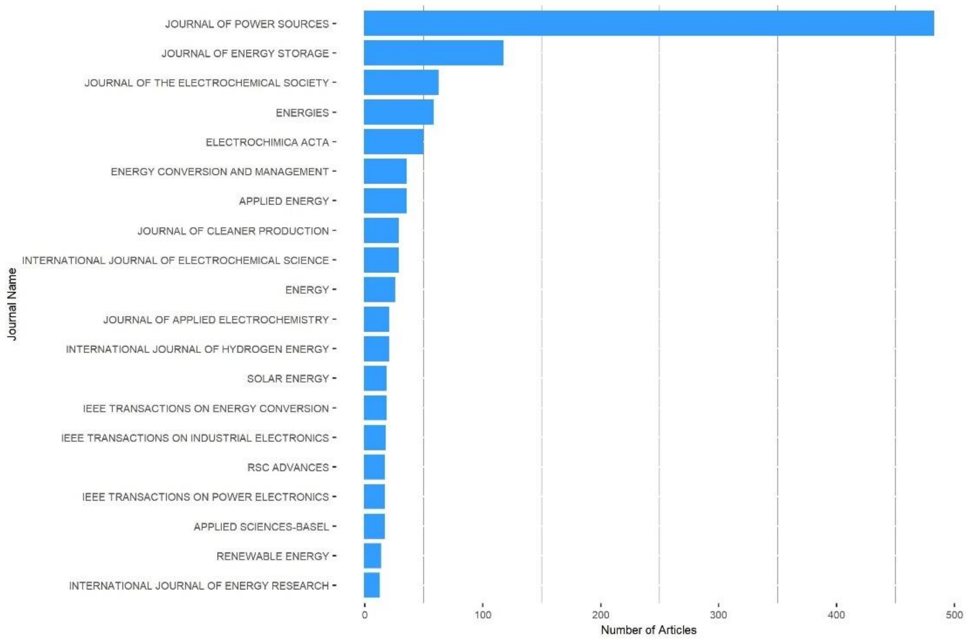

Figure 29 - Total lead-acid publications per scientific journal, 2000-2021

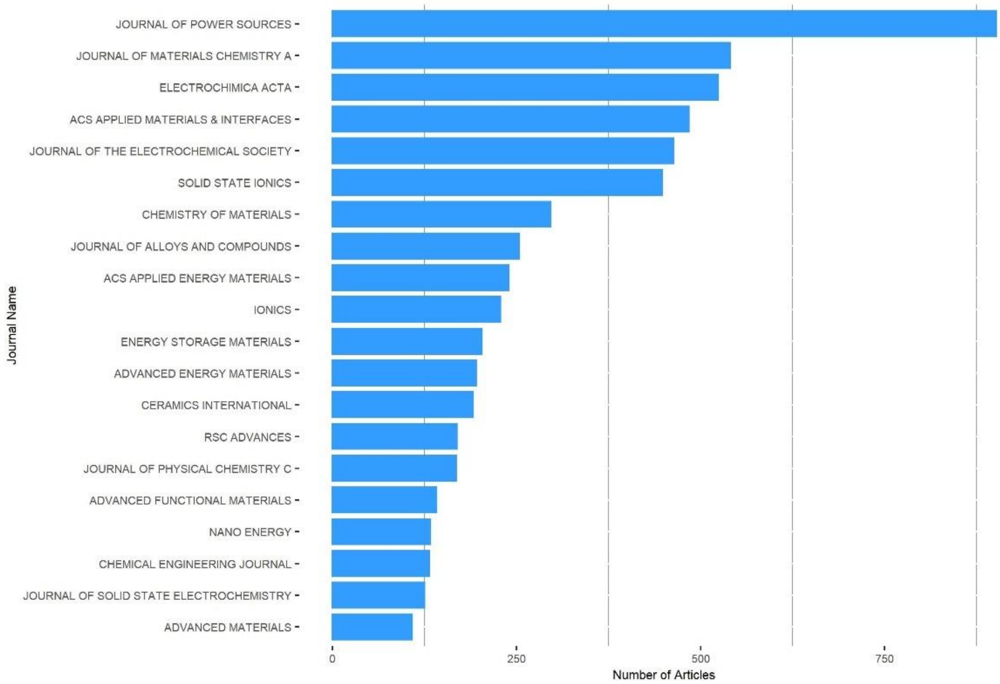

Figure 30 - Total solid-state publications per scientific journal, 2000-2021

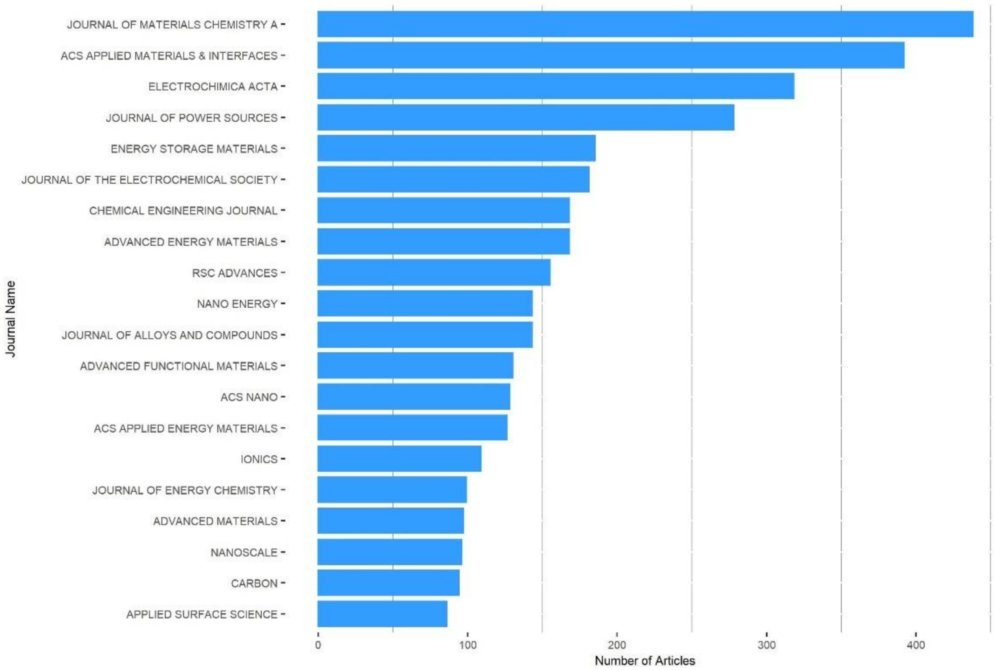

Figure 31 - Total lithium-sulfur publications per scientific journal, 2000-2021

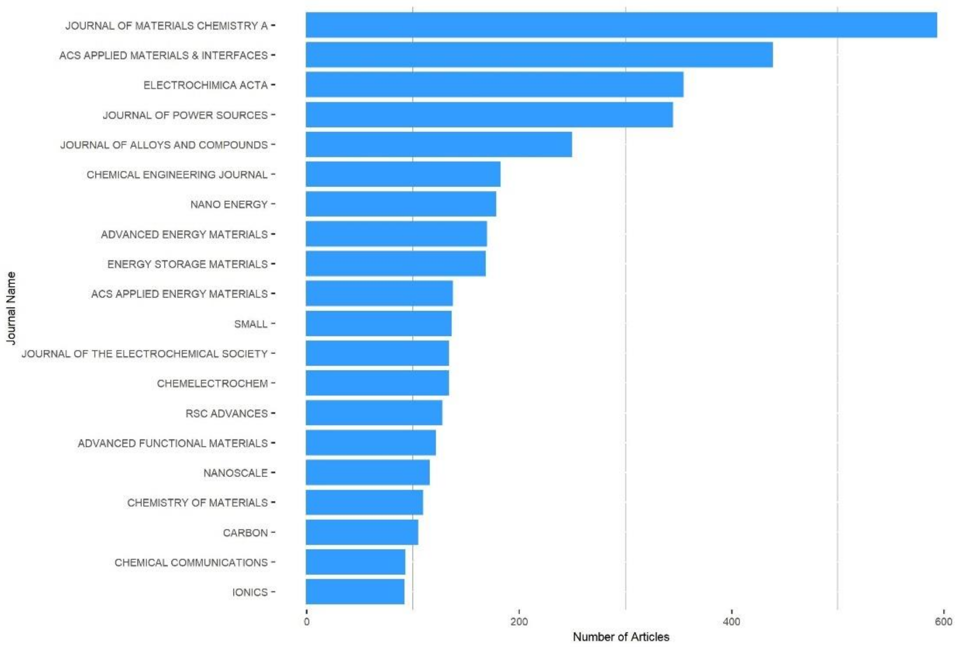

Figure 32 - Total sodium-ion publications per scientific journal, 2000-2021

4.5. G7 VS BRICS

This section showcases the publication trends of two critical intergovernmental groups: BRICS and G7. BRICS is a group of emergent economies composed by Brazil, Russia, India, China, and South Africa. Contrarily, G7 is a group of industrialized nations that includes Germany, Canada, the United States of America, France, Italy, Japan, and the United Kingdom. The goal of this analysis is to understand how these groups contributed to the academic research related to the selected technologies and how their publishing efforts have evolved in the last two decades.

4.5.1. Publication trends with all contributing countries

Below are the number of publications made by BRICS and G7 countries on the selected batteries technologies, throughout the timeframe under analysis. As seen in **Figure 33**, publications related to redox-flow batteries have been alternatively led by BRICS and G7 countries through the years. BRICS presented a higher number of publications between 2007 and 2013, however from 2014 to 2018, G7 countries had a greater volume of publications. In 2019 BRICS surpassed G7 and has since dominated the publications on this battery. As for lead-acid publications, **Figure 34** shows that up until 2011, G7 countries had an advantage over BRICS in terms of knowledge production volume. Afterwards, BRICS had a continuous increase in publications and since 2012 the group showcases a higher number of articles related to lead-acid than G7 countries. Solid-state, lithium-sulfur and sodium-ion present similar trends throughout the time period, as shown in **Figure 35**, **Figure 36** and **Figure 37**. BRICS has been the main contributor to the volume of publications related to these technologies, distancing itself from G7 countries as the timeframe progressed. Specifically in 2021, BRICS had almost twice the number of solid-state articles comparatively to G7 and ten times the number of lithium-sulfur and sodium-ion articles as the same group.

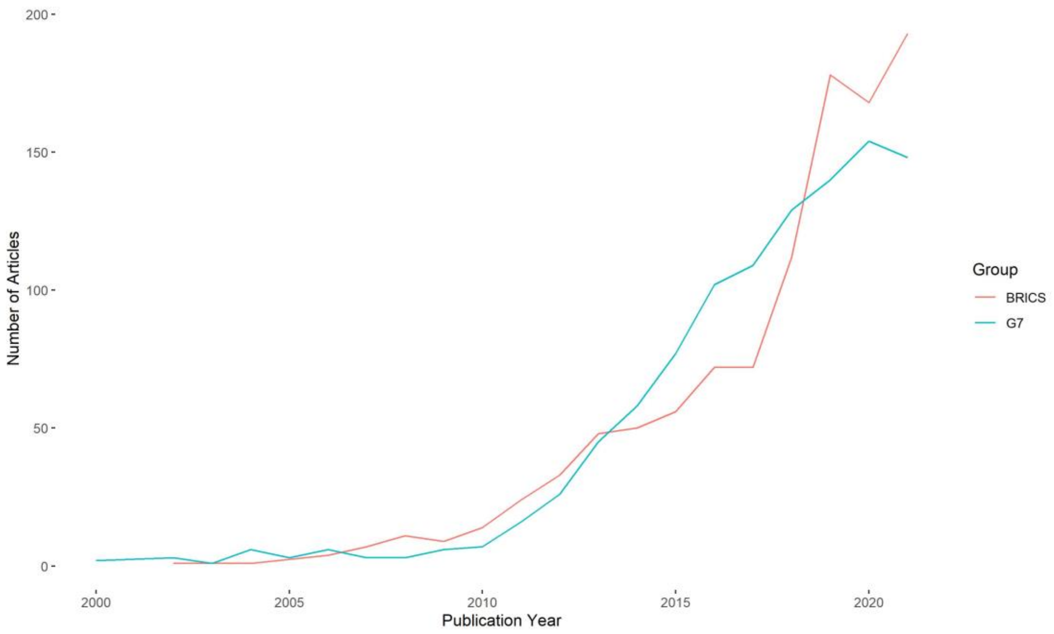

Figure 33 - Total redox-flow publications by BRICS and G7 countries, 2000-2021

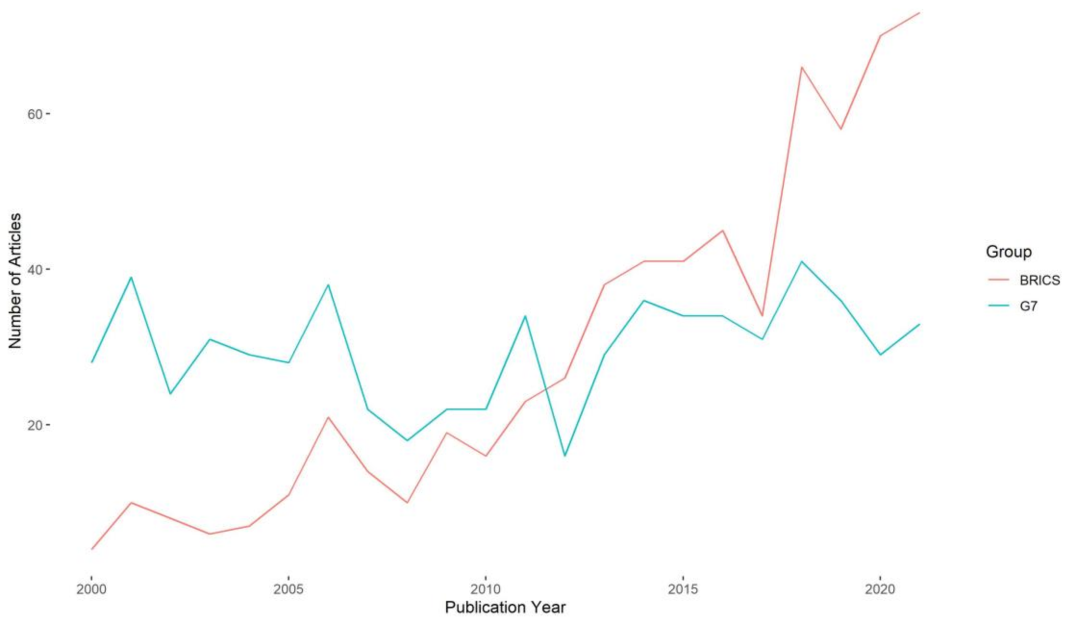

Figure 34 - Total lead-acid publications by BRICS and G7 countries, 2000-2021

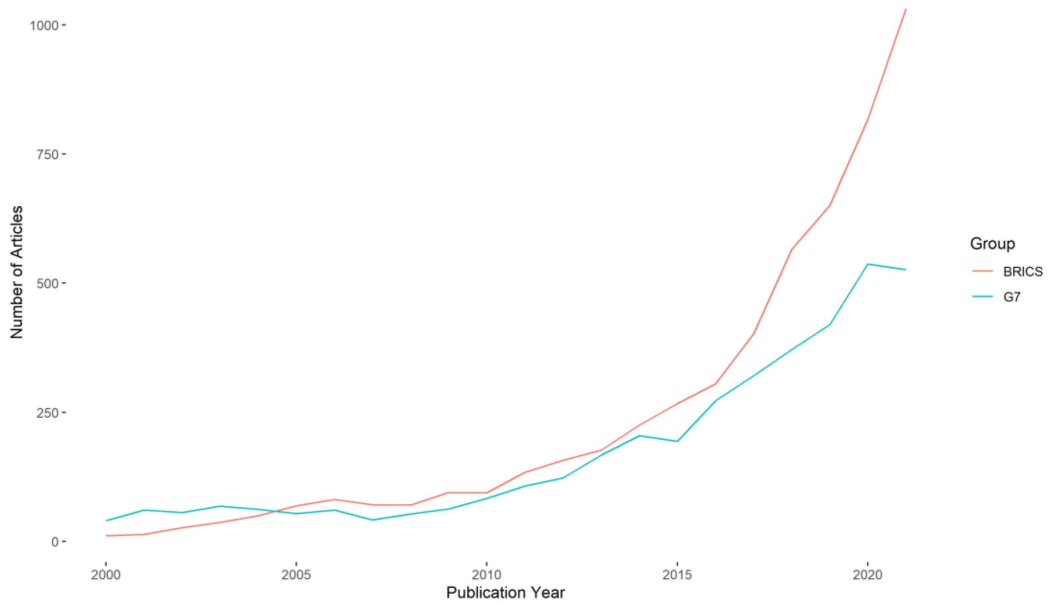

Figure 35 - Total solid-state publications by BRICS and G7 countries, 2000-2021

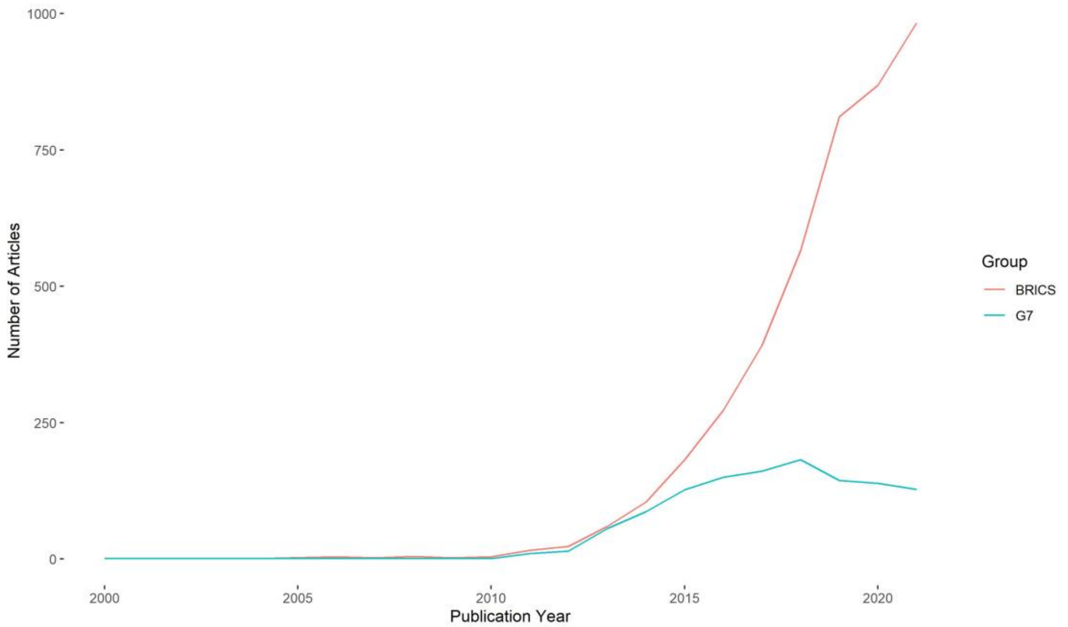

Figure 36 - Total lithium-sulfur publications by BRICS and G7 countries, 2000-2021

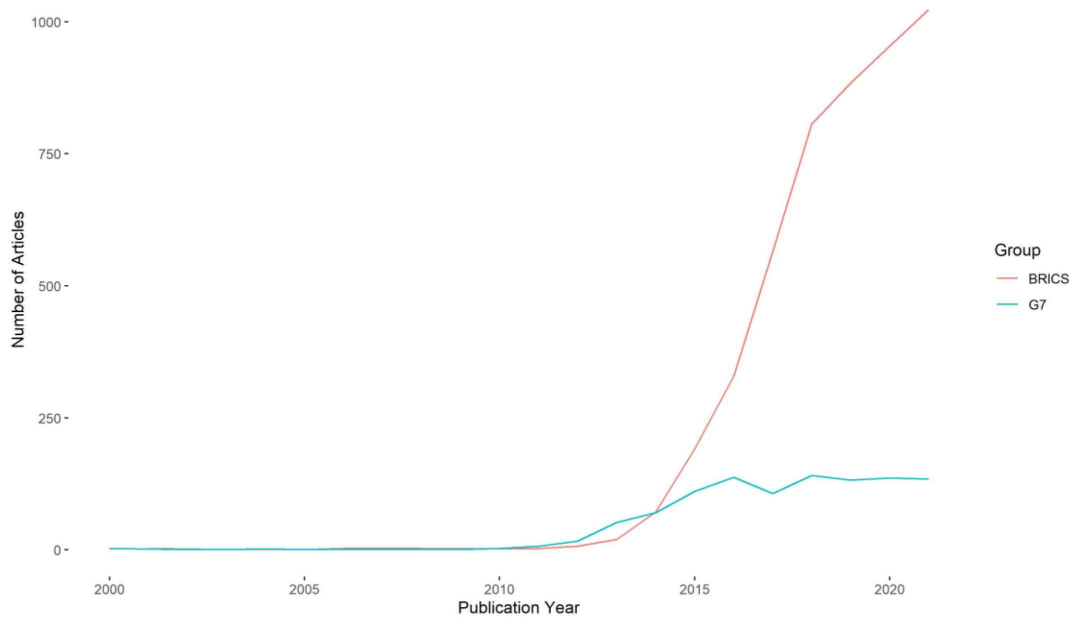

Figure 37 - Total sodium-ion publications by BRICS and G7 countries, 2000-2021

4.5.2. Publication trends without main contributing countries

A separate exercise was conducted to understand the impact in the publication trends of BRICS and G7 countries if the main contributing country in each of the groups was not considered for calculations. Therefore, China was excluded from BRICS results and the United States from G7 results. Overall, it is possible to conclude that if the main contributors are not taken into consideration, the G7 group displays a higher volume of the publications than BRICS for all battery technologies, unlike what was seen in 4.5.1. Specifically for redox-flow and solid-state batteries, G7 countries had a higher number of publications than BRICS on all years under analysis, as seen in **Figure 38** and **Figure 40**. Lead-acid publications showcase a similar trend to the previously mentioned technologies, however in 2020 BRICS surpassed the G7 group in terms of publication volume and has since dominated this technology, possibly due to the increase in India's publishing contributions in the same year, as seen before in **Figure 9**. These conclusions can be seen in **Figure 39**. The G7 group also dominated publications on lithium-sulfur and sodium-ion, with BRICS surpassing it in particular years by less than five publications, as shown in **Figure 41** and **Figure 42**. It is worth noting that in 2021 the number of publications on sodium-ion by BRICS and G7 was almost identical, which suggests a big growth from the former even without China's publishing contributions.

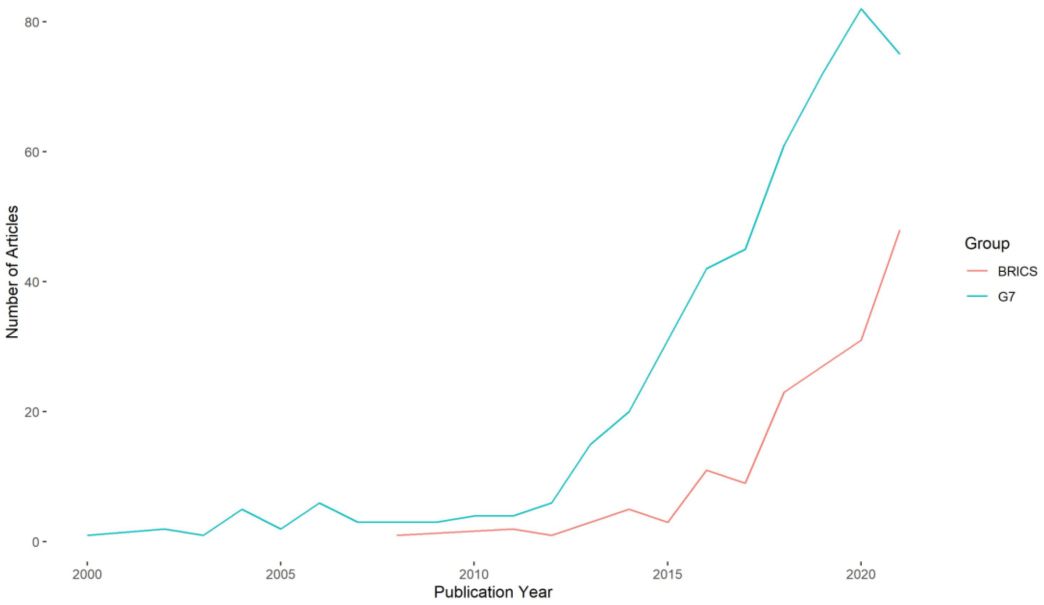

Figure 38 - Total redox-flow publications by BRICS-China and G7-USA, 2000-2021

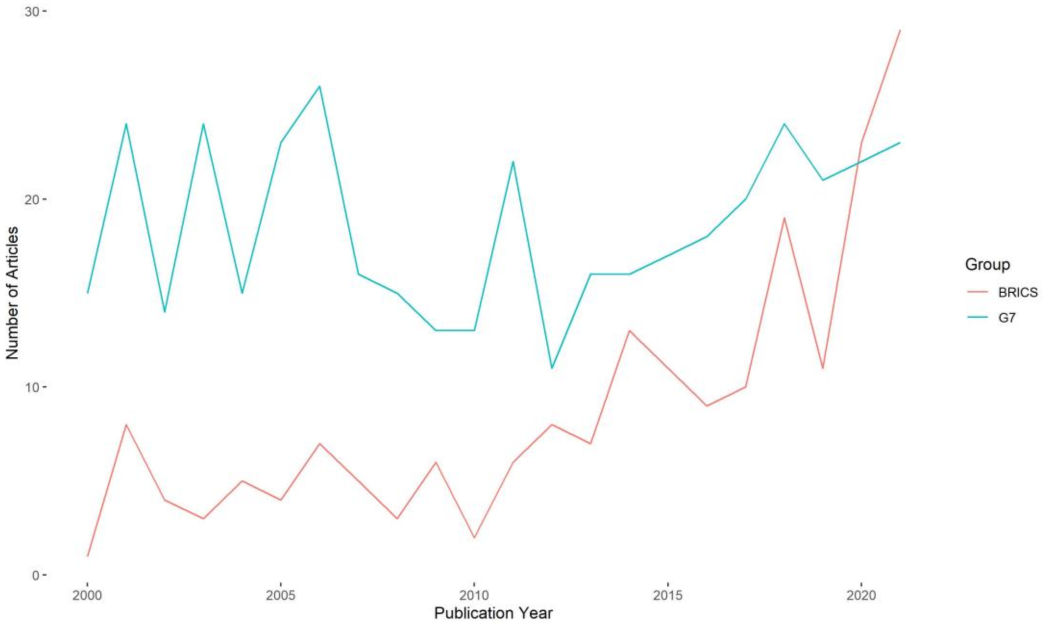

Figure 39 - Total lead-acid publications by BRICS-China and G7-USA, 2000-2021

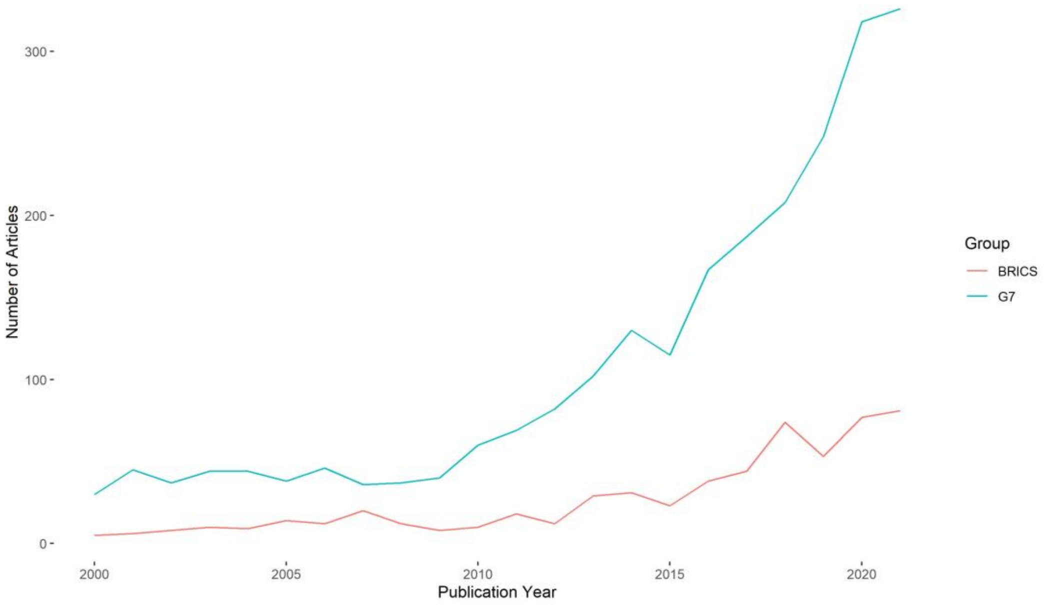

Figure 40 - Total solid-state publications by BRICS-China and G7-USA, 2000-2021

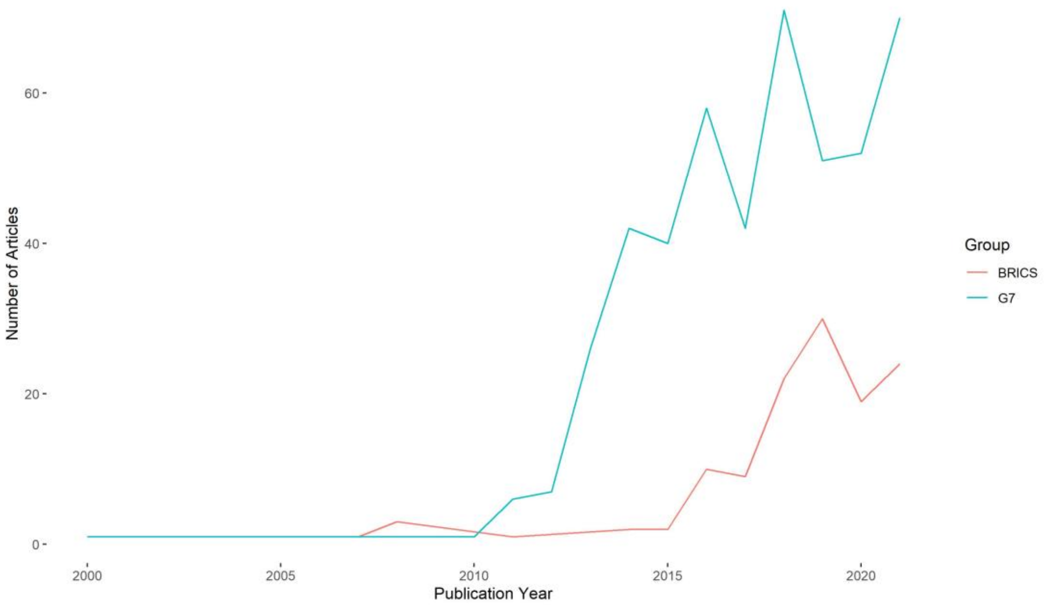

Figure 41 - Total lithium-sulfur publications by BRICS-China and G7-USA, 2000-2021

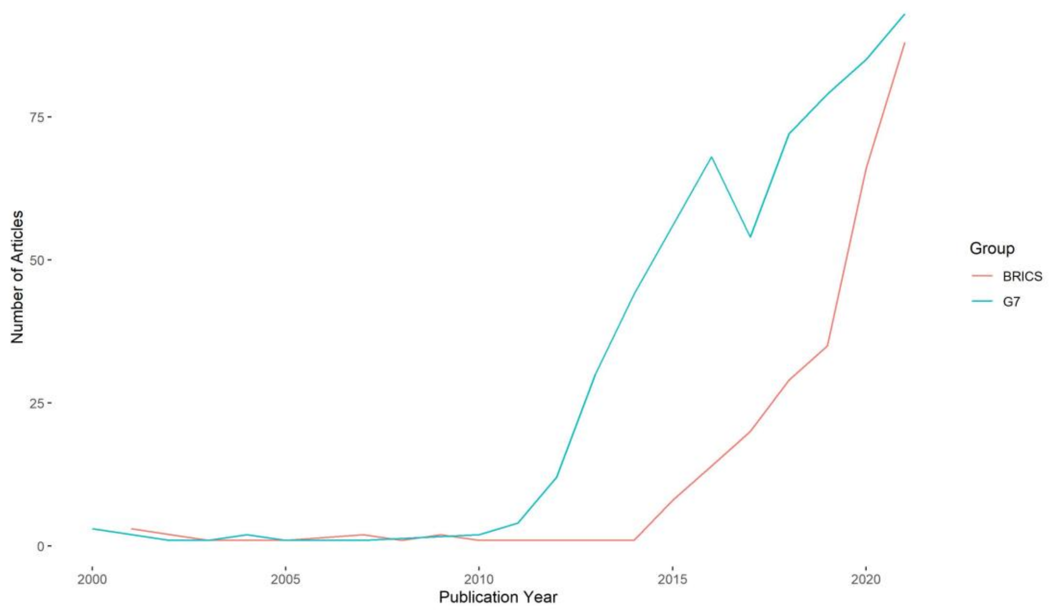

Figure 42 - Total sodium-ion publications by BRICS-China and G7-USA, 2000-2021

4.6. ARTICLE ABSTRACT MINING

The content of article abstracts is an important source of information that contributes to a thorough analysis of scientific publications. Displayed are the top 50 most frequent trigrams (three-word arrays) by battery technology and their occurrence evolution between 2000 and 2021. For organizational purposes, they were sorted in descending order by total occurrence count. Amongst trigram counts of redox-flow related abstracts are "vanadium redox flow", "aqueous redox flow" and "organic redox flow" which are allusive to variations of the redox-flow battery. The first trigram started becoming more reoccurring in the early 2010's, during the same period where redox-flow publications began to increase (see **Figure 3**). The other two trigrams only started increasing in occurrences later on the time period, around 2017. The increase of "energy storage system", "scale energy storage" and "energy storage technology" over the years hints at the expanding importance of redox-flow solutions for efficient energy storage systems. From a sustainability perspective, the increase in occurrences of "renewable energy source" and "grid scale energy" might suggest that redox-flow batteries are pro-circularity energy solutions as well as reliable options for energy accumulation to support the grid. The aforementioned results can be seen in **Figure 43**. Following the results in **Figure 44**, trigram counts of lead-acid abstracts include "hybrid energy storage" and "hybrid electric vehicle". The first word array began to appear more repeatedly in later years of the timeframe however, the latter appeared as early as 2000, with most occurrences registered until 2010. This might suggest a connection between lead-acid batteries and hybrid technology, especially for early stages of electric vehicle investigation and late stages of alternative energy storage. Other lead-acid trigrams such as "renewable energy system", "renewable energy source" and "solar home system" are allusive to the application of this battery for domestic accumulation of energy produced through renewable energy sources. All these arrays became more predominant in 2018 or after, which hints at a recent increase in the investigation of lead-acid applications for sustainable energy solutions, specifically with the integration of renewable energies. Numerous solid-state trigrams are suggestive of different battery technologies such as "lithium ion battery", "sodium ion battery", "lithium sulfur battery" and "lithium metal battery". The number of occurrences of these word arrays displayed a considerable increase throughout the time period, especially after 2010 for the first two trigrams and after 2017 for the last two. This might suggest a close association between solid-state technology and other battery types. Unlike what was seen in redox-flow and lead-acid, there are no direct references to sustainability amongst solid-state trigrams. It is worth mentioning the several occurrences of trigrams related to microscopy, which can imply an interest in investigating the material properties of this battery. These results can be found in **Figure 45**. As seen in **Figure 46**, many of the trigrams found in lithium-sulfur related abstracts are intrinsically connected to the properties of the battery itself. For example, "initial discharge capacity", "theoretical energy density" and "theoretical specific capacity", which have been growing in importance since 2016, could indicate that there has been an increase in the volume of academic investigation on these characteristics of lithium-sulfur batteries. In fact, a particular trigram is directly related to one of the main advantages of Li-S: the higher energy density comparatively to LIBs, as described in section 2.2. Additionally, trigrams such as "capacity decay rate" and "capacity fading rate" suggest a challenge in lithium-sulfur batteries which is starting to be addressed. Another interesting trigram amongst the top is "lithium ion battery". It has been growing in importance since 2011 with most occurrences happening in 2019 and 2021 which hints at the increasingly close connection between lithium-sulfur and lithium-ion research. **Figure 47** shows that similarly to some of the previous batteries, "energy storage system", "energy storage device" and "scale energy storage" are amongst the most reoccurring trigrams in sodium-ion abstracts, becoming more predominant after 2015. "lithium ion battery" also appears as one of the most common trigrams, with increased importance since 2013. This indicates that analogously to lithium-sulfur, sodium-ion and lithium-ion technologies are frequently investigated together.

Publication Year Trigrams	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
redox flow battery	2	0	5	2	8	2	13	15	17	16	29	70	82	128	158	204	277	301	402	520	543	559
vanadium redox flow	0	1	0	1	4	2	2	6	8	6	23	41	54	88	98	115	132	168	197	291	248	237
energy storage system	0	0	0	0	1	0	0	0	1	0	1	0	0	10	9	29	29	18	29	46	44	60
scale energy storage	0	0	0	0	0	0	0	0	0	0	0	1	2	4	8	13	18	20	29	27	37	39
ion exchange membrane	0	0	0	0	0	0	2	0	4	2	2	3	4	7	12	7	23	22	22	25	20	35
anion exchange membrane	0	0	0	0	0	0	0	1	1	0	5	5	6	10	15	10	12	13	14	44	15	35
vanadium ion permeability	0	0	0	0	0	0	0	3	2	0	1	2	2	6	9	13	18	25	17	33	14	19
aqueous redox flow	0	0	0	0	0	0	0	0	0	0	0	1	2	1	6	7	9	20	22	22	43	29
electrochemical impedance spectroscopy	0	0	0	0	0	0	0	1	1	3	2	1	7	10	13	7	11	13	16	22	21	17
charge discharge cycle	0	0	0	0	0	0	0	0	0	0	3	2	3	3	5	14	13	14	14	15	22	24
organic redox flow	0	0	0	0	0	0	0	0	0	0	0	1	2	0	3	0	1	11	16	20	33	40
ion exchange capacity	0	0	0	0	1	0	0	2	2	3	4	6	6	11	9	7	5	13	14	21	9	10
redox flow cell	0	0	1	4	1	1	3	0	1	2	1	8	5	4	4	6	10	12	11	8	14	12
carbon felt electrode	0	0	0	0	0	0	0	0	1	4	0	5	3	2	7	9	7	15	7	16	16	16
graphite felt electrode	0	0	1	0	0	0	0	1	1	0	0	1	0	3	6	4	11	7	12	15	18	19
flow battery system	0	0	0	0	0	0	0	0	1	1	0	1	5	3	5	7	5	6	11	16	16	12
energy storage technology	0	0	0	0	0	0	0	0	0	1	0	0	1	6	3	8	5	11	12	8	11	19
proton exchange membrane	0	0	0	0	0	0	0	0	2	0	1	0	2	4	2	4	3	9	7	23	18	10
open circuit voltage	0	0	4	0	1	0	1	0	1	3	2	2	2	2	2	6	3	8	9	15	12	9
polyether ether ketone	0	0	0	0	0	0	0	0	1	2	1	0	5	3	6	8	8	9	10	13	7	7
scanning electron microscopy	0	0	0	0	0	0	0	0	1	0	1	3	3	8	11	8	5	7	6	13	8	6
ray photoelectron spectroscopy	0	0	0	0	0	0	0	0	0	0	1	5	3	9	4	5	5	7	7	12	7	12
nonaqueous redox flow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	14	11	11	10	5	15
electrolyte flow rate	0	0	0	0	0	0	0	0	2	1	2	1	7	2	8	9	4	4	8	11	9	7
energy storage device	0	0	0	0	0	0	0	0	0	0	0	3	2	2	1	6	6	10	9	9	14	12
sulfonated polyether ether	0	0	0	0	0	0	0	0	1	1	1	0	5	2	6	7	8	9	9	13	6	5
aqueous organic redox	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	10	21	28
cation exchange membrane	0	0	0	0	0	0	0	0	2	1	5	1	0	1	3	5	6	2	10	10	11	12
electrochemical energy storage	0	0	0	0	0	0	0	0	0	0	1	0	1	1	3	3	5	6	14	11	12	11
specific surface area	0	0	0	1	0	0	0	1	0	0	0	0	1	2	1	4	6	2	5	14	15	14
renewable energy source	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	5	6	7	12	8	11	13
redox active material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	11	4	9	13	10	13
vanadium redox reaction	0	0	0	0	1	0	0	0	0	0	0	2	1	1	4	5	5	7	10	6	14	7
density functional theory	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	4	5	3	5	6	13	18
ether ketone speek	0	0	0	0	0	0	0	0	1	1	1	1	4	2	5	5	6	8	6	8	5	4
charge discharge cycling	0	0	0	0	0	0	0	0	1	0	0	3	1	2	0	1	5	6	6	6	13	10
charge transfer resistance	0	0	0	0	0	0	0	1	0	1	1	1	0	1	1	4	3	11	9	8	5	6
lithium ion battery	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	5	2	5	4	7	8	13
bromine redox flow	0	0	0	0	0	0	0	0	0	1	0	0	1	3	6	3	7	2	6	6	3	12
vanadium ion crossover	0	0	0	0	0	0	0	1	0	0	1	0	0	2	0	6	5	3	5	16	5	5
oxygen functional group	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	1	2	5	3	17	9	6
grid scale energy	0	0	0	0	0	0	0	0	0	0	0	1	2	0	3	2	3	9	5	5	6	11
redox active species	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	7	4	8	9	7	7
peak power density	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	6	0	4	5	15	12
charge discharge performance	0	0	0	0	0	0	0	1	0	0	0	0	3	5	3	9	2	4	4	6	2	5
charge discharge test	0	0	0	0	0	0	0	0	0	0	0	2	3	4	3	2	4	5	4	4	9	4
flow battery based	0	0	0	0	0	0	0	0	1	0	0	1	1	3	3	4	3	6	2	5	6	9
electrical energy storage	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	6	5	3	7	12	3	4
fourier transform infrared	0	0	0	0	0	0	0	0	0	1	0	1	3	4	5	3	1	4	5	6	3	5
modified graphite felt	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	0	5	5	10	7	7

Figure 43 - Trigram occurrences in redox-flox related article abstracts

Publication Year Trigrams	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
lead acid battery	56	60	51	59	60	68	107	59	61	90	63	101	73	130	119	130	158	143	206	229	193	251
valve regulated lead	16	18	14	23	21	12	13	11	5	12	4	11	2	13	6	5	12	11	17	5	6	17
energy storage system	0	3	0	1	0	0	2	1	0	5	3	2	9	7	14	12	10	19	27	32	29	49
lithium ion battery	0	0	0	0	2	2	2	4	2	1	7	8	14	18	12	4	11	12	16	26	26	34
lead acid cell	2	1	3	2	6	3	3	3	2	4	6	1	6	3	2	1	4	6	7	14	9	12
spent lead acid	1	1	0	0	0	2	0	0	0	1	1	2	4	12	3	5	10	10	6	12	13	8
scanning electron microscopy	1	0	2	1	2	1	5	3	4	8	3	1	0	5	5	4	9	8	7	6	5	4
electrochemical impedance spectroscopy	0	0	2	2	1	0	4	1	3	6	3	7	3	4	2	2	4	4	7	5	8	12
nickel metal hydride	1	0	2	1	6	5	5	3	0	3	3	6	8	0	5	1	4	5	3	3	4	3
hybrid electric vehicle	2	2	0	3	6	4	3	5	4	7	3	4	3	2	0	2	4	2	6	2	1	3
rate partial state	0	0	0	0	1	2	1	3	0	1	2	0	6	5	4	4	7	4	9	5	4	7
battery energy storage	0	4	1	0	0	1	0	1	0	0	2	1	0	3	2	6	3	5	9	5	10	11
energy storage technology	0	0	0	1	0	0	0	0	0	0	1	0	3	3	4	6	6	2	8	5	7	7
hybrid energy storage	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	1	2	5	8	9	6	14
open circuit voltage	0	0	0	1	0	1	3	0	4	2	0	2	2	4	1	4	2	2	3	6	1	8
charge discharge cycle	0	1	0	0	1	2	1	0	3	1	2	1	3	1	4	6	3	3	4	4	2	1
sulfuric acid solution	0	2	0	2	4	1	3	2	4	6	3	2	2	0	0	1	2	1	3	0	3	2
renewable energy system	0	0	0	0	4	0	0	1	0	1	0	2	1	0	0	1	2	0	1	5	13	11
energy storage device	0	0	1	0	1	1	1	1	2	3	1	0	1	0	3	0	4	4	6	7	3	2
power supply system	0	0	0	1	0	2	3	1	0	2	0	3	1	6	1	0	6	0	10	2	0	2
renewable energy source	0	0	0	0	0	0	0	0	0	0	0	1	0	0	4	2	3	2	4	9	6	9
maximum power point	1	0	0	1	1	0	0	0	0	0	0	2	1	5	0	7	3	1	7	2	4	4
conventional lead acid	1	1	0	0	0	2	6	1	0	1	1	3	2	1	2	1	1	0	4	8	1	2
battery management system	0	0	0	1	0	3	0	1	0	0	0	2	1	3	0	0	2	0	5	2	10	7
blood lead levels	1	0	0	3	0	2	0	2	2	0	0	1	4	4	3	3	2	0	2	1	3	3
flooded lead acid	1	2	1	1	1	1	0	0	3	3	0	1	0	6	4	0	1	0	6	1	2	2
specific surface area	1	0	1	0	1	3	3	0	1	1	0	2	1	0	0	0	1	3	1	3	7	6
spent lead paste	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	1	6	4	3	9	7	2
net present cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	3	1	4	2	8	11
vanadium redox flow	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	0	1	9	3	2	11
redox flow battery	0	0	0	0	0	0	1	0	0	0	0	0	0	3	2	1	1	2	8	2	4	7
life cycle assessment	0	0	0	0	0	1	0	4	2	0	0	0	0	0	0	4	0	3	3	4	4	5
hydrogen evolution reaction	0	3	0	0	0	0	1	2	0	1	0	1	0	5	3	3	1	1	3	2	1	2
acid battery bank	0	0	0	0	0	0	0	1	2	0	2	1	1	1	1	2	0	2	4	8	2	1
sealed lead acid	3	1	1	1	1	1	4	1	1	1	0	1	2	1	0	1	2	0	4	0	1	1
acid battery paste	0	0	0	0	0	0	0	0	0	2	0	0	2	7	0	1	3	1	0	7	3	0
power point tracking	1	0	0	1	0	0	0	0	0	0	0	1	1	3	0	2	3	1	3	2	3	4
oxygen evolution reaction	0	1	0	0	0	0	0	2	2	3	0	1	5	6	0	0	0	0	2	1	1	1
solar home system	0	1	0	2	0	2	2	1	0	0	0	2	0	0	0	0	0	1	6	4	3	1
acid battery system	1	1	0	0	1	0	0	0	0	1	0	1	0	0	2	0	3	1	2	7	5	0
active material utilization	0	0	1	0	1	0	2	1	0	3	1	1	2	2	5	1	0	0	2	1	1	0
acid battery industry	1	0	1	1	1	0	1	2	1	3	0	1	1	0	0	3	2	1	1	0	1	3
lead sulfate crystal	2	5	1	0	1	0	0	2	0	0	0	1	1	0	0	2	3	1	3	0	1	1
internal combustion engine	1	0	1	1	2	0	0	0	4	1	1	1	0	0	0	1	1	0	3	5	0	1
membrane fuel cell	1	0	0	0	0	1	1	2	2	0	0	2	3	3	2	1	3	1	0	0	0	1
hybrid power system	0	0	0	0	0	0	0	0	0	2	2	4	0	0	1	4	3	0	1	4	1	1
waste lead acid	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	2	0	2	6	4	6
proton exchange membrane	1	0	0	0	0	1	1	0	1	0	0	2	3	2	2	1	3	1	0	0	1	3
lithium iron phosphate	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	3	3	5	1	1	7
acid battery pack	0	0	0	0	0	0	2	1	0	1	2	4	1	0	1	0	2	0	2	2	2	1

Figure 44 - Trigram occurrences in lead-acid related article abstracts

Publication Year Trigrams	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
solid state battery	10	8	7	4	14	12	8	11	20	8	17	38	40	50	62	89	147	216	363	478	721	783
solid state reaction	17	31	39	46	52	66	81	55	72	76	76	117	154	136	176	180	176	175	142	139	150	139
lithium ion battery	8	9	12	8	12	25	28	23	20	32	34	63	82	102	134	156	184	216	227	268	318	320
solid state lithium	4	4	4	16	12	18	7	12	7	13	23	20	36	43	70	67	108	121	210	261	376	438
solid state electrolyte	0	1	2	2	7	1	5	3	5	7	13	19	9	26	40	53	73	100	165	238	364	439
scanning electron microscopy	0	4	5	9	12	16	20	16	26	34	36	36	61	50	68	67	70	76	47	58	69	67
state lithium battery	1	2	1	8	9	4	2	5	3	2	5	8	10	12	25	26	42	50	91	117	149	185
initial discharge capacity	0	2	3	3	7	12	14	9	15	21	27	26	27	44	53	49	47	42	56	62	59	70
solid polymer electrolyte	1	3	1	2	3	8	7	1	8	2	3	4	2	17	7	25	25	49	70	98	134	154
sodium ion battery	0	0	0	0	0	0	2	0	2	0	0	0	4	15	25	32	50	63	72	101	87	101
electrochemical impedance spectroscopy	0	2	2	1	2	2	7	4	8	11	12	18	33	37	36	44	57	60	42	59	55	58
energy storage device	0	0	0	0	0	0	1	2	0	0	2	2	6	7	10	16	28	56	78	94	119	110
quasi solid state	0	0	1	1	0	0	0	0	1	1	0	1	5	9	4	8	17	39	57	86	136	149
transmission electron microscopy	0	3	4	2	3	5	6	8	12	11	23	29	42	25	39	42	38	42	31	33	61	48
state lithium ion	0	1	1	2	0	2	1	2	1	3	4	4	7	11	19	23	40	49	65	64	90	83
solid state cell	0	2	5	5	4	2	4	7	10	14	19	20	18	23	22	22	23	33	43	50	44	54
lithium metal battery	0	0	0	0	0	0	0	0	0	1	1	1	0	1	2	2	0	13	29	60	131	174
poly ethylene oxide	1	7	1	6	1	6	8	4	4	4	4	4	3	7	14	8	17	24	42	71	81	85
ray photoelectron spectroscopy	1	3	2	3	1	4	2	6	6	5	6	7	9	11	15	26	29	37	38	45	65	76
temperature solid state	3	4	6	3	4	5	5	12	9	12	10	10	7	15	15	21	25	31	42	33	37	48
nuclear magnetic resonance	1	6	4	4	4	3	2	6	2	5	6	8	7	13	10	20	27	33	25	30	46	61
conventional solid state	0	4	13	5	6	4	13	5	7	7	10	13	17	27	26	20	24	19	26	15	27	28
charge discharge cycle	5	3	4	3	4	1	3	7	2	4	8	5	10	19	18	20	30	28	22	34	40	37
density functional theory	1	0	0	0	0	0	1	2	1	0	1	0	2	5	5	10	14	19	37	47	74	81
lithium sulfur battery	0	0	0	0	0	0	1	0	0	0	1	1	3	4	4	12	19	26	38	52	66	71
galvanostatic charge discharge	0	2	1	2	1	6	5	6	4	9	9	11	16	23	30	36	33	29	16	11	15	17
energy storage system	1	0	0	0	0	0	0	0	1	1	0	1	2	4	7	7	12	17	41	48	58	74
state lithium metal	0	0	0	1	0	1	0	0	0	0	0	1	1	2	1	0	0	8	21	37	86	111
charge transfer resistance	1	2	1	4	1	5	7	2	1	4	2	8	9	18	24	34	18	24	20	22	35	24
flexible solid state	0	0	0	0	0	0	0	0	0	0	0	0	2	4	5	16	16	27	48	46	53	47
composite polymer electrolyte	0	1	5	7	11	4	2	6	3	6	6	8	4	4	18	2	8	11	18	40	43	55
solid state synthesis	1	1	6	1	1	1	6	1	7	1	6	8	11	13	25	17	23	23	28	27	30	19
solid state sodium	0	0	0	0	0	0	1	0	1	0	0	0	2	1	3	7	5	15	39	40	59	72
based solid state	0	0	0	1	0	1	1	0	0	0	1	2	2	2	7	11	5	16	29	36	65	66
electrochemical stability window	0	0	0	2	5	1	1	1	1	2	3	2	2	5	3	5	10	16	23	30	48	56
scanning electron microscope	1	2	0	1	3	3	9	9	5	7	4	9	15	18	13	16	9	14	18	13	13	22
oxygen reduction reaction	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	3	6	20	23	41	51	58
thin film battery	0	16	4	6	3	8	14	4	5	6	16	9	3	7	11	12	7	11	18	16	16	11
solid state diffusion	1	5	1	3	0	3	3	0	4	6	3	5	8	12	11	15	9	19	21	22	27	22
lithium ion conductivity	0	0	1	2	5	7	7	1	2	1	1	6	5	10	4	3	12	15	30	22	25	36
gel polymer electrolyte	2	1	1	1	2	0	2	1	6	1	0	1	0	0	2	7	7	20	41	24	29	45
zinc air battery	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	1	5	16	33	42	40	51
based solid electrolyte	0	1	0	0	0	1	1	0	0	2	0	0	4	8	6	3	7	9	18	32	37	56
specific surface area	2	3	1	0	1	0	13	5	1	9	3	0	9	5	7	12	9	17	15	19	23	29
fourier transform infrared	0	0	1	0	5	1	6	10	2	5	4	4	5	9	14	13	13	17	13	18	26	16
solid state thin	1	5	7	5	7	8	14	8	5	12	9	5	7	6	10	9	7	10	12	7	12	13
solid state polymer	0	2	0	0	0	0	6	1	2	3	2	1	4	2	8	3	10	10	16	26	36	46
state thin film	1	5	7	5	7	8	14	7	5	12	10	5	7	6	10	9	6	9	12	7	12	13
step solid state	0	1	1	2	1	4	4	1	6	2	10	13	17	12	12	16	13	13	14	15	8	11
state nuclear magnetic	0	1	3	0	3	1	2	3	2	1	1	3	0	7	4	10	21	21	10	16	24	42

Figure 45 - Trigram occurrences in solid-state related article abstracts

Publication Year	2000	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Trigrams																					
lithium sulfur battery	1	4	3	2	0	3	1	5	2	5	41	31	115	181	295	397	590	779	1048	1106	1276
initial discharge capacity	0	0	0	0	0	1	1	0	1	1	4	1	13	24	41	53	54	105	110	82	97
energy storage system	0	0	0	0	0	0	0	0	0	1	3	4	2	5	16	27	45	77	98	104	136
energy storage device	0	0	0	0	0	0	0	0	0	0	0	0	3	2	19	21	50	64	84	89	110
theoretical energy density	0	0	0	0	0	0	0	0	0	0	1	1	5	4	16	23	31	71	67	74	96
lithium ion battery	0	0	0	0	1	0	0	0	0	0	2	6	7	13	14	43	39	51	73	63	73
generation energy storage	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	13	28	48	76	77	108
specific surface area	0	0	0	2	0	0	0	0	1	0	0	3	8	14	18	27	36	41	54	73	66
density functional theory	0	0	0	0	0	0	0	1	0	0	0	0	2	5	6	16	26	39	60	76	96
reduced graphene oxide	0	0	0	0	0	0	0	0	0	0	0	5	2	10	11	26	56	48	67	50	36
lithium sulfur cell	0	0	3	1	1	3	3	2	0	0	1	13	11	17	27	29	18	34	28	23	31
performance lithium sulfur	0	0	0	0	0	0	0	0	0	0	0	0	2	5	10	17	30	31	47	42	45
initial specific capacity	0	0	0	0	0	0	0	0	0	0	0	0	2	4	3	13	17	28	42	48	48
theoretical specific capacity	0	0	0	0	0	0	0	0	0	0	0	0	4	6	7	19	19	34	38	34	44
capacity decay rate	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	5	13	24	48	37	73
scanning electron microscopy	0	1	2	0	0	0	1	0	2	2	0	9	14	16	18	18	16	13	27	26	16
solid state lithium	0	0	0	0	0	0	0	0	0	0	0	1	4	5	6	11	10	19	40	41	42
sulfur host material	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	14	18	38	42	61
charge discharge process	0	0	0	0	0	0	0	0	0	0	0	0	5	8	17	13	16	21	34	29	31
solid state battery	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	2	22	24	40	37	33
nitrogen doped carbon	0	0	0	0	0	0	0	0	0	0	0	0	1	4	6	1	11	26	32	38	41
energy density battery	0	0	0	0	0	0	0	0	0	0	0	0	3	4	6	8	15	21	30	30	38
ray photoelectron spectroscopy	0	0	0	0	0	0	0	0	0	0	1	6	4	4	10	13	18	18	26	26	28
polysulfide shuttle effect	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	13	8	27	23	39	39
state lithium sulfur	0	0	0	0	0	0	0	0	0	0	0	1	4	5	6	10	9	17	28	34	38
electrochemical energy storage	0	0	0	0	0	0	0	0	0	0	0	1	4	1	10	13	18	20	23	29	31
discharge specific capacity	0	0	0	0	0	1	0	0	1	0	0	0	4	2	6	7	11	9	25	35	44
charge discharge cycle	0	0	0	0	1	0	1	0	0	0	1	3	8	11	10	10	15	16	22	22	24
lithium metal anode	0	0	0	0	0	0	0	0	0	0	0	2	3	3	10	14	8	26	25	23	26
stable cycling performance	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	9	16	13	23	34	34
electrochemical impedance spectroscopy	0	0	0	2	0	0	0	0	0	1	1	9	8	10	16	19	7	11	17	21	12
capacity fading rate	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	4	5	17	30	37	38
functional theory calculation	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	6	10	18	29	30	37
rechargeable lithium sulfur	0	0	0	0	0	1	1	1	0	0	1	6	7	8	15	12	14	14	24	8	16
solid electrolyte interphase	0	0	0	0	0	0	0	0	0	0	0	0	2	2	12	7	16	19	25	22	22
soluble lithium polysulfides	0	0	0	0	0	0	0	0	0	0	0	2	2	1	7	6	10	13	18	28	38
doped porous carbon	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	5	18	17	28	18	19
areal sulfur loading	0	0	0	0	0	0	0	0	0	0	0	0	0	5	2	6	18	23	21	15	21
energy storage technology	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	11	12	10	21	27	19
transmission electron microscopy	0	0	0	0	0	0	0	0	0	1	1	4	7	10	15	7	11	15	17	11	3
hierarchical porous carbon	0	0	0	0	0	0	0	0	0	0	3	0	2	3	8	11	17	13	12	10	20
energy density lithium	0	0	0	0	0	0	0	0	0	0	1	0	0	2	3	3	12	13	13	24	23
term cycling stability	0	0	0	0	0	0	0	0	0	0	0	0	4	1	3	5	9	12	20	15	24
physics chinese academy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3	13	31	42
chemical physics chinese	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3	13	31	42
specific discharge capacity	0	0	0	0	0	0	0	0	0	0	0	0	1	4	6	11	14	9	12	14	22
sluggish redox kinetics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	14	32	42
rapid capacity fading	0	0	0	0	0	0	0	0	0	1	0	0	5	3	4	9	10	13	18	10	17
strong chemical interaction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	7	16	21	22	19
density lithium sulfur	0	0	0	0	0	0	0	0	0	0	1	0	0	2	3	2	11	11	11	23	23

Figure 46 - Trigram occurrences in lithium-sulfur related article abstracts

Publication Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Trigrams																						
sodium ion battery	1	1	3	0	1	0	2	0	2	1	1	9	19	99	210	444	661	917	1257	1377	1385	1460
lithium ion battery	0	0	0	1	0	1	0	1	0	0	0	2	2	14	21	82	114	173	188	239	216	245
sodium ion storage	0	0	0	0	0	0	0	0	0	0	0	0	0	4	8	15	45	68	76	91	106	102
reduced graphene oxide	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6	25	46	57	94	69	67	68
scale energy storage	0	0	0	0	0	0	0	0	0	0	0	0	1	6	9	18	22	49	85	68	74	67
energy storage device	0	0	0	0	0	0	0	0	0	0	0	0	1	2	5	13	33	47	60	78	73	71
density functional theory	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	10	20	26	49	69	83	96
energy storage system	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	11	21	36	48	73	72	75
sodium storage performance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	15	39	66	59	73	77
initial coulombic efficiency	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	11	20	38	39	63	65	62
transmission electron microscopy	0	0	0	0	0	0	0	0	0	0	0	0	1	1	6	27	38	43	36	53	46	42
nitrogen doped carbon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	17	16	28	56	54	50
specific surface area	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	6	13	33	40	45	33	47
initial discharge capacity	0	0	0	0	0	0	0	0	2	0	0	0	0	1	5	16	20	24	32	48	33	38
lithium sodium ion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	7	20	26	50	55	38
scanning electron microscopy	0	0	0	0	0	0	0	1	2	0	0	1	0	3	5	22	26	25	30	36	22	25
ray photoelectron spectroscopy	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	9	11	21	29	43	40	40
reversible specific capacity	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	10	20	29	28	25	31	43
electrochemical impedance spectroscopy	0	0	0	0	0	0	0	1	0	0	0	0	1	3	6	17	13	25	21	39	23	37
term cycling stability	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	6	14	23	33	22	42	39
electrochemical energy storage	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	3	11	27	24	28	43	39
performance sodium ion	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	3	16	15	34	34	36	34
sodium ion diffusion	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	3	7	33	30	39	26	30
solid state reaction	0	0	0	0	0	0	1	0	1	0	0	0	3	3	7	15	21	13	27	24	29	31
rechargeable sodium ion	1	0	1	0	0	0	0	0	0	0	0	2	1	4	8	14	23	20	27	27	29	16
charge discharge process	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4	15	15	36	30	32	37
potassium ion battery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	13	36	35	76
ion battery anode	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	7	15	21	33	29	27	26
functional theory calculation	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	6	11	27	34	35	45
aqueous sodium ion	0	0	0	0	0	0	0	0	0	0	0	2	1	3	8	15	20	22	22	27	14	18
solid electrolyte interphase	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	11	15	14	23	26	26	34
sodium ion full	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	11	11	26	32	35	31
charge discharge cycle	0	0	0	1	0	1	0	1	0	0	0	0	0	6	4	19	11	14	12	22	21	22
ion full cell	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	9	11	23	24	27	28
transition metal oxides	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	6	12	13	26	20	22	22
sodiation desodiation process	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	13	18	17	28	25	17
sodium storage property	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	15	17	16	28	19	23
sodium storage mechanism	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	7	7	8	19	28	22	27
solid state sodium	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	3	3	9	22	16	22	37
performance anode material	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	12	18	24	18	17	21
poor cycling stability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	8	7	26	19	24	20
sodium ion capacitors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	5	11	25	15	21	23
stable cycling performance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	4	10	11	21	25	19	11
based anode material	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	7	7	13	21	25	28
sodium storage capacity	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	7	13	12	8	25	25	12
ether based electrolyte	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	7	18	26	26	11	13
ray absorption spectroscopy	0	0	0	0	0	0	0	0	0	0	0	0	2	4	1	5	4	14	9	19	22	17
theoretical specific capacity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	10	14	12	27	29
galvanostatic intermittent titration	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	6	9	10	14	21	33
charge transfer resistance	0	0	0	0	0	0	0	0	0	0	1	0	0	2	1	11	5	11	17	13	22	12

Figure 47 - Trigram occurrences in sodium-ion related article abstracts

4.7. THE CIRCULAR DYNAMICS OF BATTERY RESEARCH

Article data provides essential information to characterize not only the scientific participants involved in topic research but also the studied subject itself. The goal of this analysis is to expand the current research by evaluating the degree to which sustainability and circular economy were considered in the literature. The keywords chosen as representative of the circular thematic were: "circular economy", "sustainability", "sustainable", "eco-friendly", "green innovation" and "eco innovation". There is a total of 1149 articles (approximately 2.5% of the total of 46411 publications) that include this terminology and therefore serve as the basis of this specific analysis.

Publications with circular terminology displayed increasing and decreasing publishing trends up until 2014. This was also a time period with a relatively low volume of published articles, with less than 50 publications each year. However, since 2015 the number of published articles has been progressively increasing, reaching 300 publications in 2021.

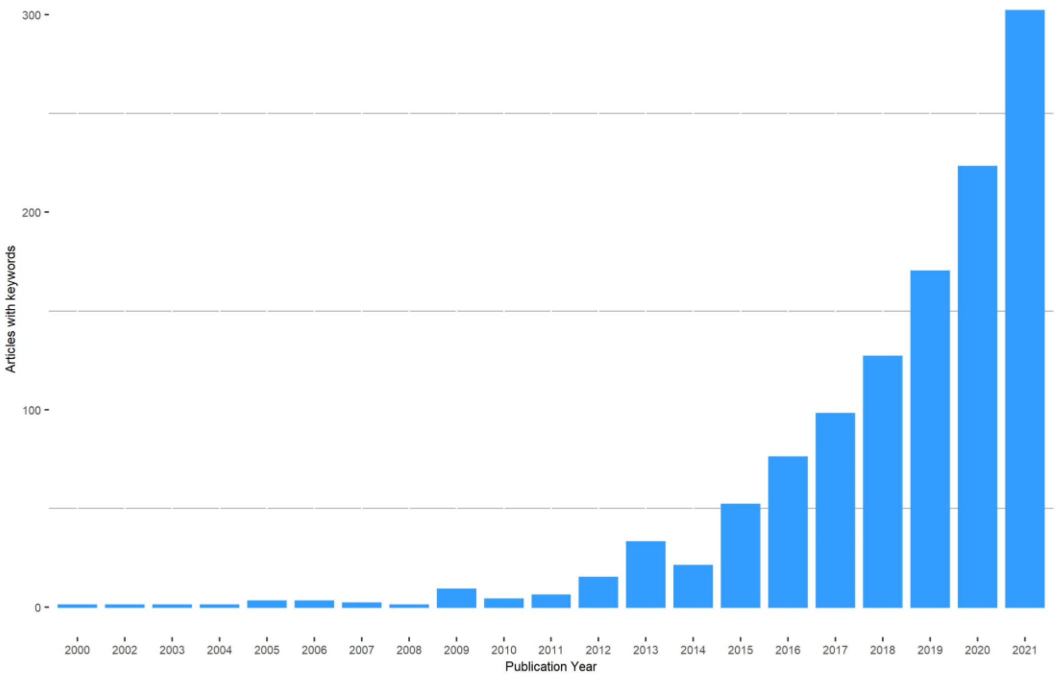

Figure 48 - Total number of publications with circular terminology, 2000-2021

China has generally dominated circularity publications throughout the time period under study. The country was only surpassed in 2014 and 2016 by the United States of America with less than 5 articles of difference. After 2016 publications made by China grew immensely and the country distanced itself from the other top countries. The USA was the second top country publishing on circularity matters up until 2020. In 2021 it was surpassed by South Korea which showed a considerable growth in publication volume, comparatively to previous years. These results can be seen in **Figure 49**.

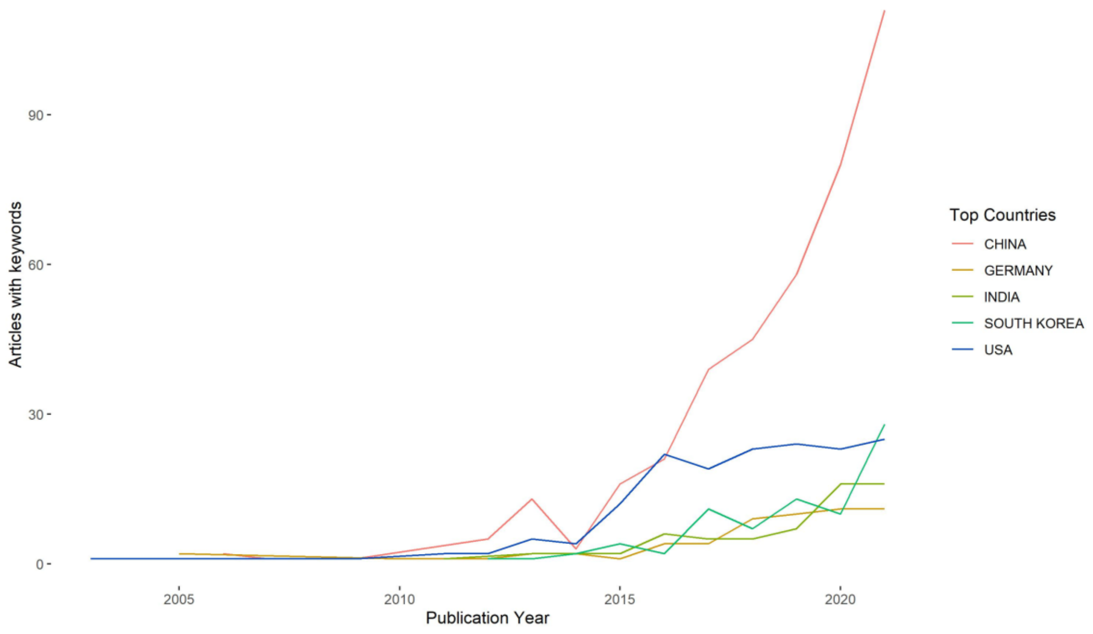

Figure 49 - Total circular publications per first author's country of affiliation, 2000-2021

Despite determining from **Figure 49** that China published the majority of scientific articles on sustainability matters, **Figure 50** shows that most top authors are actually associated with the Americas, more specifically with North America. The first three authors are all connected to the Utah State University. Only four Asian authors are present amongst the top contributors, which are either related to Soochow University or Nanjing University. As for Europe there are two authors from the University of Cordoba, in Spain.

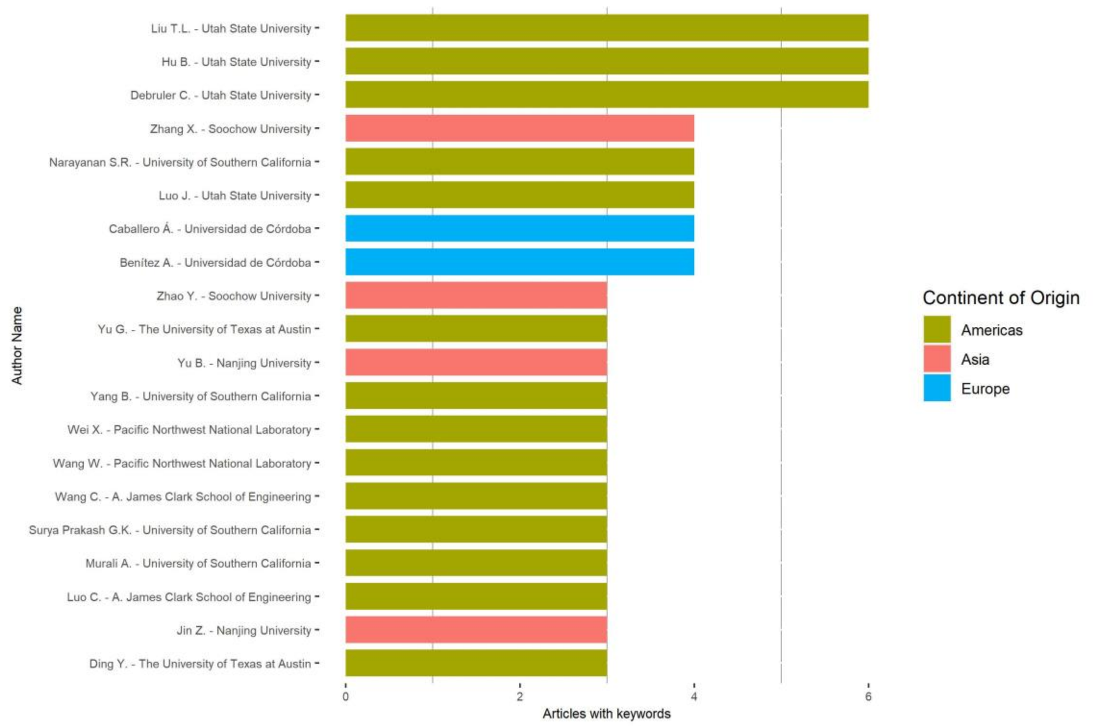

Figure 50 - Total circular publications per author by continent of affiliation, 2000-2021

The top affiliations publishing on battery related circularity and sustainability affairs are the Utah State University and the Pacific Northwest National Laboratory, which are both American institutions. They are followed by two Chinese organizations: the Soochow University and the Tsinghua University. As seen in **Figure 50** both the Utah State University and the Soochow University are associated with the top authors publishing on this thematic. Amongst the top there are also three Spanish affiliations including the University of Cordoba, which is also connected to top authors. There are two South Korean institutions and a single Australian affiliation: the Griffith University. These trends can be seen in **Figure 51**.

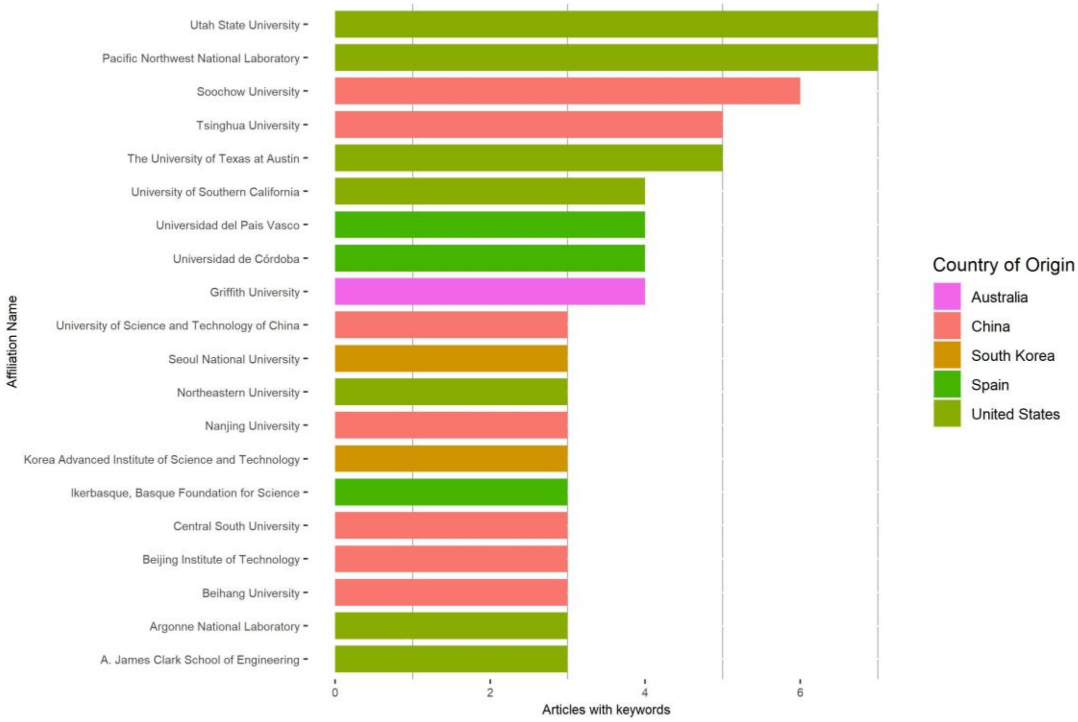

Figure 51 - Total circular publications per affiliation by country of origin, 2000-2021

The most reoccurring trigram in circularity related abstracts is “sodium ion battery” which started to increase in frequency in 2015. There are also other trigrams indicative of battery types amongst the first ten word arrays, namely “lithium ion battery”, “redox flow battery”, “lithium sulfur battery” and “lead acid battery”. This suggests that four of the five battery technologies under study are commonly found in circularity abstracts and therefore might be connected to research on sustainable energy matters. “solid state battery” is also found in the main trigrams, however it appears in the 21th position with a substantially lower number of occurrences, comparatively to the other battery trigrams. Other reoccurring trigrams are “energy storage system”, “energy storage device”, “sustainable energy storage” and “renewable energy source” which have all increased in incidence specially on the second half of the 2010s. While the last two trigrams are undoubtedly related to circularity and sustainability, the first two indirectly hint at these matters by implying a higher concern with ensuring efficient energy storage. These trends can be seen in **Figure 52**.

Publication Year	2000	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Trigrams																					
sodium ion battery	0	0	0	0	0	0	0	0	0	0	0	0	1	3	22	19	20	26	58	42	63
lithium ion battery	0	0	0	0	0	0	0	0	0	0	2	7	4	4	11	18	20	15	46	45	74
energy storage system	0	0	0	0	0	0	0	0	0	0	0	2	3	6	3	11	11	13	24	32	51
redox flow battery	0	0	0	0	0	0	0	0	0	0	1	0	2	3	1	6	9	13	21	31	23
energy storage device	0	0	0	0	0	0	0	0	0	0	2	1	2	1	2	9	8	17	12	22	31
lithium sulfur battery	0	0	0	0	0	0	0	0	0	0	0	1	1	0	5	11	19	9	18	12	18
lead acid battery	0	0	1	0	1	1	0	0	1	1	5	0	7	1	7	4	3	15	6	13	26
sustainable energy storage	0	0	0	0	0	0	0	0	0	0	0	1	2	1	2	8	6	6	6	20	26
energy storage technology	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	12	5	4	4	11	11
electrochemical energy storage	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	5	8	9	4	6	14
scale energy storage	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	1	5	10	6	10	11
renewable energy source	0	0	0	0	0	0	0	0	0	0	1	0	0	2	3	1	4	7	7	9	12
organic electrode material	0	0	0	0	0	0	0	1	0	0	0	0	2	0	1	2	3	4	5	15	13
density functional theory	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	3	8	3	8	13
specific surface area	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	2	6	2	5	5	8
life cycle assessment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	1	2	8	10
redox active organic	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	1	2	2	7	10
charge discharge cycle	0	0	0	0	0	0	0	0	0	0	1	1	1	0	4	0	1	3	6	4	5
electrical energy storage	0	0	0	0	0	0	0	0	0	0	0	1	1	2	0	3	3	5	3	4	3
vanadium redox flow	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	3	14	4
solid state battery	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	0	0	4	2	8	6
potassium ion battery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	10	1	10
organic redox flow	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	4	3	6	4
reduced graphene oxide	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	4	2	5	1	6
organic cathode material	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	3	6	4	5
solid state lithium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	3	8	3	2
ion battery technology	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	9	1	6
oxygen evolution reaction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	7	8
sodium ion storage	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	2	2	4	1	6
material flow analysis	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	2	2	4	2	5
battery energy storage	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	3	3	10
quasi solid state	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	8
initial discharge capacity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	5	6	3	1	0
ray photoelectron spectroscopy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	5	3	6
renewable energy system	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	2	11
stationary energy storage	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	3	6	5
oxygen reduction reaction	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	10	2
solid state electrolyte	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	6	6
electrochemical impedance spectroscopy	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	4	2	4	1
battery electric vehicle	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	7	1	4
scanning electron microscopy	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	1	2	2	2	2	3
metal ion battery	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	5	4	4
hybrid energy storage	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	2	9
doped porous carbon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	1	3	3	3
nitrogen doped carbon	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	7	2	3
initial coulombic efficiency	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	2	3	0	4
nuclear magnetic resonance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	1	5	5
energy storage material	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	2	0	1	2	6
aqueous sodium ion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	1	3	0	1
hybrid renewable energy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	11

Figure 52 - Trigram occurrences in circularity related article abstracts

4.7.1. Circular keywords occurrences

This specific analysis further investigates the extent to which circularity matters are investigated in each battery technology. A number of keywords usually associated with circularity and sustainability were searched for on article abstracts related to each battery. To ensure that the assessment captured all relevant occurrences, the search for each keyword included not only the word itself but also related variations. For example, the search for occurrences of “downcycling” also took into consideration the occurrences of words like “downcycled” and “downcycle”.

The circular keyword with most incidence in all battery abstracts is “reduce”. For redox-flow, lithium-sulfur and sodium-ion it became more frequent after 2013 and gradually increased in relevance until 2021, as seen in **Figure 53**, **Figure 56** and **Figure 57**, respectively. However, for lead-acid and solid-state abstracts it has been registered several times since the beginning of the time period. This trend in shown in **Figure 54** and **Figure 55**. Another common keyword is “renew”, which has more incidence in redox-flow, lead-acid and sodium-ion publications. Similarly to the word “reduce”, it also started to become more predominant around 2013, with most occurrences being registered in 2021. This keyword was searched together with “renewable”, one of the most commonly associated words with the circularity thematic. Therefore, this might justify the increasingly higher number of occurrences. “durable” is also one of the most common words in abstracts related to redox-flow, solid-state, lithium-sulfur and sodium-ion but unlike the previous keywords, it only started to become more relevant on the second half of the 2010’s. There are two circularity terms that display a significant number of occurrences in lead-acid abstract but not in any other battery: “recover” and “recycle”. Both these terms were first documented in 2000 and have since increased in incidence, with most occurrences being registered after 2015.

Redox flow	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	total
Cradle-to-cradle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Decoupling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	5	9	6	7	11	44
Downcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Durable	0	0	1	0	0	0	0	0	1	0	0	1	1	1	7	6	4	7	10	18	22	22	101
End-of-life	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
e-Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Extendend producer responsibility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lifecycle	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	5	1	2	3	7	9	8	37
Metabolism	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	2
Recover	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	1	3	6	4	8	7	33
Recycle	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	2	2	8	0	15
Redesign	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reduce	0	1	0	0	1	0	0	5	3	2	3	4	8	14	21	33	44	36	53	79	82	91	480
Renew	0	0	0	0	0	0	1	0	0	1	2	2	4	6	6	13	22	26	34	33	48	54	252
Repair	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Reuse	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	4	0	5
Symbiosis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
Technical nutrients	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Urban mining	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	2	2	7	3	17

Figure 53 - Circular keywords occurrences in redox-flow publications, 2000-2021

Lead-acid	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	total
Cradle-to-cradle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Decoupling	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	3
Downcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Durable	0	0	1	0	1	0	1	0	0	1	1	0	1	0	3	0	2	1	3	3	3	4	25
End-of-life	0	2	0	1	0	1	1	1	0	0	1	0	0	0	0	2	0	3	2	1	7	2	24
e-Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	4
Extendend producer responsibility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lifecycle	0	0	2	1	1	2	1	3	0	2	4	4	2	2	2	6	4	11	10	9	14	16	96
Metabolism	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	2	0	0	0	4
Recover	2	1	3	1	1	1	3	1	3	7	5	2	6	7	1	6	10	12	12	25	17	16	142
Recycle	2	2	0	3	3	5	4	4	1	3	6	5	3	10	4	8	19	10	15	25	25	17	174
Redesign	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	3
Reduce	6	10	5	11	6	8	14	2	4	16	5	9	11	17	17	17	27	23	35	39	53	47	382
Renew	0	1	1	0	3	1	2	1	0	1	3	3	6	5	6	10	11	13	15	24	21	28	155
Repair	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	1	1	1	2	8
Reuse	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	5	1	3	7	6	26
Symbiosis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Technical nutrients	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Urban mining	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste	1	1	0	0	1	0	1	1	1	1	2	2	3	3	0	2	7	4	7	15	15	9	76

Figure 54 - Circular keywords occurrences in lead-acid publications, 2000-2021

Solid-state	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	total
Cradle-to-cradle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Decoupling	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	2	2	5	4	2	7	27
Downcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Durable	0	0	0	1	0	0	0	0	0	0	1	3	1	3	5	9	3	10	18	24	60	55	193
End-of-life	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1	4
e-Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extendend producer responsibility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Lifecycle	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	1	2	1	1	3	1	2	14
Metabolism	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recover	2	0	0	3	2	1	2	2	0	0	3	1	3	6	6	5	11	5	0	12	8	15	87
Recycle	1	0	0	1	0	0	0	0	0	0	0	0	1	0	2	2	1	6	9	8	7	8	46
Redesign	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	1	4
Reduce	6	4	7	13	7	7	15	14	8	15	14	24	29	48	48	73	75	120	147	163	199	249	1285
Renew	0	0	1	0	1	0	0	1	0	0	1	0	3	3	3	0	3	4	8	9	7	15	59
Repair	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	1	1	6
Reuse	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	1	0	1	1	5	1	12
Symbiosis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Technical nutrients	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Urban mining	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	4	4	2	5	9	5	4	36

Figure 55 - Circular keywords occurrences in solid-state publications, 2000-2021

Lithium-sulfur	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	total
Cradle-to-cradle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Decoupling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	1	1	1	7
Downcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Durable	0	0	0	0	0	0	1	0	0	0	0	0	2	0	1	2	7	7	15	16	28	31	110
End-of-life	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
e-Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extendend producer responsibility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lifecycle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	5	2	2	6	18
Metabolism	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recover	0	0	0	0	0	0	1	0	0	0	0	0	0	0	3	3	5	4	7	8	7	7	45
Recycle	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	5	5	6	3	8	10	40
Redesign	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2
Reduce	1	0	1	1	0	0	0	0	1	0	0	4	9	19	34	43	61	111	120	179	189	176	949
Renew	0	0	0	0	0	0	0	0	0	0	0	1	1	1	5	3	5	12	2	6	9	7	52
Repair	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1	0	4	8
Reuse	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3	3	5	6	6	25
Symbiosis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Technical nutrients	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Urban mining	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	9	11	5	16	16	16	79

Figure 56 - Circular keywords occurrences in lithium-sulfur publications, 2000-2021

Sodium-ion	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	total
Cradle-to-cradle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Decoupling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	1	4
Downcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Durable	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	4	12	14	27	24	40	37	161
End-of-life	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	1	5
e-Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Extendend producer responsibility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lifecycle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	1	0	4	8	18
Metabolism	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	2
Recover	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	4	8	7	10	13	9	58
Recycle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	3	2	6	3	7	12	36
Redesign	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	2
Reduce	0	0	0	1	1	0	0	0	0	1	0	0	1	12	12	50	64	106	165	150	163	185	911
Renew	0	0	0	0	0	0	0	0	0	0	0	0	0	5	4	2	7	17	25	21	23	29	133
Repair	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	3
Reuse	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2	1	2	3	10
Symbiosis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Technical nutrients	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upcycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Urban mining	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	4	6	9	18	12	19	72

Figure 57 - Circular keywords occurrences in sodium-ion publications, 2000-2021

5. DISCUSSION

Looking at the results in 4.1.1, one could argue that the stable increase in article production for the batteries under study could stem from the homologous interest in researching and developing technologies that are able to tackle the disadvantages of lithium-ion.

Examining section 4.1.2, it was determined that for every battery technology, China is the country that displays the most significant growth in terms of publication volume throughout the years. It was also inferred that China is the main contributor to the publication volume of all batteries. However, by analyzing the results displayed in 4.2 and 4.3 it can be concluded that even though China is indisputably the country with the most overall publications, it does not imply that the main authors and affiliations are also associated with this country. For example, looking at **Figure 19** and **Figure 24**, it is clear that most lead-acid top authors and affiliations are actually linked to European countries. This is related to the fact that lead-acid is one of the main technologies dominating the European battery market, which can be explained by considering that lead-acid batteries are commonly used in conventional combustion engine vehicles, a technology that is still prevalent in the European motor industry. This technology is also a critical example of efficient battery recycling since lead-acid units are currently recycled with an efficiency above 99% in the European Union, thus motivating investigation on recycling techniques for other technologies (Yanamandra et al., 2022). Another example is the solid-state battery, displayed in **Figure 20** and **Figure 25**, where many of the top authors and institutions are associated with Japan. This is due to the expanding academic interest around this disruptive battery technology, likely motivated by the contemporary industrial innovation intended by Japanese motor companies. Toyota has introduced one of the first electric vehicles (EV) powered by solid-state batteries which is expected to be a trustworthy alternative to lithium-ion powered EVs for its lower risk of fire and higher energy density. This can also explain the fact that the Toyota Motor Corporation is one of the main institutions publishing on this battery (see **Figure 25**). Nissan, another Japanese motor company, also has plans to develop its own solid-state battery for electric vehicle applications.

Concerning the journal trends in section 4.4, it was established that the *Journal of Power Sources* and the *Journal of Materials Chemistry A* are the main publishers of articles related to the battery technologies under study. These journals publish mainly on matters of electrochemical power and materials with energetic applications, respectively. Interestingly, these two journals are also part of the global top 50 journals publishing in the category of Renewable Energy, Sustainability and the Environment. In 2021, the *Journal of Materials Chemistry A* was in the 12th position of the ranking while the *Journal of Power Sources* was in the 24th position. Other, less predominant journals are also publishing on the theme. For example, *Applied Energy*, which publishes generally on energy conversion and conservation, appears amongst the main journals publishing on redox-flow and lead-acid (see **Figure 28** and **Figure 29**) and shows up in the 13th position of the same ranking. Similarly, *Advanced Energy Materials*, which focuses on materials for energy conversion and storage, is amongst the top journals of all batteries, except lead-acid, and it was the third main journal publishing on sustainability matters in 2021. This clearly points to a relationship between the academic research on these battery technologies and environmental issues.

The results in section 4.5.1 show that BRICS has surpassed the G7 countries in terms of publication volume, which is correlated to the fact that China is included in this group. As seen before, China is one of the main countries publishing about the batteries under analysis. It is also expected to be one of the main individual contributors in terms of developments towards renewable energy and green economy by BRICS (Gu et al., 2018). This justifies the findings in 4.5.2 that by removing China from the calculations, the G7 countries actually surpass BRICS in terms of publication volume, even without considering the contributions made by the USA.

The trigrams recovered from article abstracts give us some detailed insight into what topics are actually being researched in each of the batteries. The analysis suggests that all technologies under study have grown in relevance over the years and are transforming into more reliable storage systems, capable of meeting today's energetic demands. There seems to be a close academic relationship between some of the technologies, with direct reference to other battery types in all results displayed in section 4.6. For instance, "lithium-ion battery" appears in both lithium-sulfur and sodium-ion abstracts which can be justified by the fact that these batteries share key elements and primary materials. The presence of pro-circularity terms, especially in redox-flow and lead-acid trigrams can indicate a growing interest in these technologies as more sustainable energy systems.

The results in section 4.7 point to an increase in research on sustainable energy storage solutions, with favorable projections for circular economy approaches. There are signs of recent interest on redox-flow, lead-acid, lithium-sulfur, and sodium-ion batteries as emergent technologies in the sustainable energy field. Batteries created with different materials are a potential solution to tackle one of the main disadvantages of the predominant lithium-ion battery: the rising concerns with the availability and distribution of lithium resources (Baum et al., 2022). The result in **Figure 52** that "sodium ion battery" is the top trigram in circularity related trigrams can be related to the fact that sodium is an exceptionally abundant natural resource which can be obtained at a low cost and provide considerable safety. Additionally, sodium-ion and lithium-ion units share battery components, have similar electrochemical reaction mechanisms and sodium can provide a close performance to that of lithium. This makes sodium-ion a direct alternative to lithium-ion batteries (Sawicki & Shaw, 2015)(Yi et al., 2021).

Whilst research on energy storage devices has been typically focused on performance matters, the path towards a more circular energy approach should also concentrate on investigating and designing batteries that can be recycled at low cost with an analogous environmental impact (Tan et al., 2021). Effective recycling strategies should be contemplated throughout all steps of the battery life cycle, starting with early stages of production and material extraction. Producers should prioritize recycled materials to manufacture batteries, as well as ensure appropriate labelling to facilitate sorting and recycling. Consumers can also contribute by assuming the responsibility of correctly disposing any type of electronical devices. Different recycling methods also need to be defined to account for the numerous battery types and subsequent materials (McMichael & Henderson, 1998). Public policies are also a useful strategy to regulate and ensure recycling efforts. In 2006, the European Union released the Battery Directive as part of the Sustainable Development Strategy. The goal was to standardize recycling practices and minimize the harmful impact of battery waste (Mancha, 2016). Other practical recycling policies have already been put in place, however, they sometimes still rely heavily on complex methods usually based on high-temperatures or solvents. The path towards a more environmentally friendly, green recycling approach is connected to the development of straightforward and efficient recycling technologies that can tackle the challenges brought on by current practices. Also, an attempt should be made to reduce the recovery costs and increase the quality of battery recycling data for future policy formulation. Finally, to reduce the environmental impact, eco-conscious electrolyte systems, membranes and other components should be used in battery design and production (Lin et al., 2022).

6. CONCLUSION

This study is centered on a thorough two-decade bibliometric analysis of scientific publications associated to the chosen battery technologies: redox-flow, lead-acid, solid-state, lithium-sulfur and sodium-ion. It complements and adds new perspectives to the latest bibliometric-based studies conducted on the theme.

First, from 2000 to 2021, the global publication activity of redox-flow, solid-state, lithium-sulfur and sodium-ion displayed a continuous increase in number of released articles whereas lead-acid showcased a rather irregular growth trend. Moreover, the number of countries participating in scientific publications grew significantly throughout the years, however, China stands out for being the leading nation in terms of publication volume for all battery technologies.

Second, the majority of top authors publishing on redox-flow, solid-state, lithium-sulfur and sodium-ion are associated to the Asian continent. Lead-acid publications stray from this trend and are mostly dominated by authors linked to European institutions due to the fact that this battery type is one of the main technologies in the European battery market. There is a high diversity in the geographical distribution of the main institutions participating in publications for all batteries, with the exception of lithium-sulfur which is exclusively dominated by Chinese institutions. While redox-flow, solid-state and sodium-ion publications are largely related to institutions from countries like China, the USA or Japan, the scientific production on lead-acid technology is mostly associated with European institutions from countries such as the United Kingdom, Sweden, or Germany. In terms of Journals, redox-flow, lead-acid and solid-state articles are predominantly published by the *Journal of Power Sources* which focuses on electrochemical power research, while lithium-sulfur and sodium-ion publications are primarily released by the *Journal of Materials Chemistry A*, that publishes typically on materials for energetic purposes.

Third, during the time period under study, BRICS countries surpassed the G7 group in terms of publication volume for all battery types. However, by discarding from the analysis the main contributing country from each international group, the aforementioned trend shifts. Without considering the scientific contributions of China (BRICS) and the United States (G7), G7 registered an overall higher publication volume than the BRICS group, for all technologies.

Fourth, the abstract mining analysis revealed that the association between the battery technologies and certain energy applications such as energy storage systems and energy storage devices, increased between 2000 and 2021. This indicates that the rechargeable batteries under study are growing in importance as efficient solutions for improved energy storage. Only redox-flow and lead-acid publications have direct references to sustainable energy concepts, with increasing mentions of renewable energy sources throughout the years. Additionally, lead-acid is connected to innovative technologies such as hybrid electrical vehicles and systems with solar energy integration which reiterates the role of this battery in new, more ecological applications.

Fifth, until 2014, the volume of publications associated with circular economy was relatively low, with fluctuating trends throughout the years. However, from 2015 onwards, it displayed a continuous increase in scientific production, thus confirming the growing interest in sustainability matters. China is the country with most published articles on the subject, significantly distancing itself from the other leading contributors after 2016. Despite this fact, the majority of top authors and affiliations publishing on sustainability issues are associated with North America, more specifically with the United States. The text mining analysis on circularity related publications revealed that four out of the five technologies under study are highly connected to circular economy and sustainability topics. Those are sodium-ion, redox-flow, lithium-sulfur and lead-acid batteries. Markers of circular economy in battery research seem to be linked to reduce and renew concepts, possibly due to the correlation between renewable energy sources and sustainable energy storage applications. Therefore, there are some indicators of increased interest in circularity matters, particularly associated to efforts for renewable energy integration.

All things considered, this study has been able to uncover and characterize scientific research patterns with important implications for all battery technologies. Primarily, understanding the main drivers of research, as well as who are the main contributors and what subjects are being investigated helps to identify research gaps and opportunities for new inquiry in future investigation, thus contributing to a more thorough knowledge of these batteries and related technologies. Also, this study has shown that the relationship between energy storage and circular economy was only recently started to be looked into. Even though batteries are not the sole element capable of supporting the integration of circularity policies, they are still an important key for the implementation of improved energy storage systems that facilitate the integration of renewable energy sources into the grid. Therefore, it is imperative to increase the investment on battery research from a circular economy standpoint, so to expand the current literature and encourage the development of energy storage solutions that can tackle the challenges brought on by the global energy transition.

7. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORKS

In regard to limitations, it is evident that article data can only reflect the research developments made on the selected battery technologies from an academic standpoint. Scholarly publications are known to be useful sources of information to characterize the knowledge produced about a certain research field, however they provide a narrow view of innovation from an industrial perspective. Moreover, only five emergent batteries were selected for this analysis though there are numerous other technologies that can be considered candidates for the post-lithium-ion era, not only for providing an improved performance but also for being manufactured with non-lithium resources.

Therefore, future research could benefit from investigating additional battery alternatives as well as from extending the analysis to take into consideration both the academic and industrial knowledge perspectives.

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