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Review

Energy Storage in Carbon Fiber-Based Batteries: Trends and Future Perspectives

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Abstract: Carbon fiber-based batteries, integrating energy storage with structural functionality, are emerging as a key innovation in the transition toward energy sustainability. Offering significant potential for lighter and more efficient designs, these advanced battery systems are increasingly gaining ground. Through a bibliometric analysis of scientific literature, the study identifies three primary research areas: (i) the development of anodes for lithium-ion batteries, tackling challenges such as dendrite formation and performance degradation; (ii) the creation of new carbon fiber-based cathodes with coatings of $LiFePO_4$, $LiCoO_2$, or other nanoparticles, alongside efforts to develop cobalt-free alternatives; and (iii) the advancement of solid electrolytes that achieve a balance between ionic conductivity and mechanical strength. These advancements position carbon fiber-based batteries as promising solutions for seamless integration into various structural applications. The analysis of publication trends, citation patterns, and collaboration networks provides critical insights into the ongoing technological developments, current research challenges, and emerging trends in this field. Moreover, the study highlights potential research directions, underscoring the importance of continuous innovation to fully realize the potential of carbon fiber-based energy storage technologies.

Keywords: batteries; carbon-fiber; structural composites; bibliometric analysis; review

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1. Introduction

Nowadays, there is an increasing concern about global sustainability and the growing energy demand. A significant focus has been placed on reducing CO_2 emissions, which are known to be highly detrimental to human health and the integrity of various ecosystems. Thus, the development of advanced energy storage technologies has become a critical area of research [1–3]. Battery systems are now being tailored to meet specific needs: low-current, long-duration applications like clock circuits; medium-current uses such as mobile devices; and high-current demands like electric vehicles and drones. In this regard, battery electric vehicles and drones are now attracting the interest of industry as they significantly reduce urban air pollution [4,5]. Among the materials being investigated for energy storage applications, carbon fibre stands out as a particularly promising candidate [6–8].

Carbon fiber, traditionally utilized in the aerospace, automotive, and sports equipment industries, possesses unique structural characteristics that enable the development of multifunctional materials. These materials can simultaneously serve as both the structural component and the energy storage medium [9–11]. As a result, conventional heavy batteries can be either replaced by or integrated into carbon fiber-based batteries, allowing them to fulfill both structural and energy storage roles. For instance, they could be incorporated into the trunk of a car or the fuselage of an airplane, leading to significantly lighter and more efficient designs [7,12–14]. The ability of carbon fibers to be coated into various forms and integrated with other active materials further enhances their versatility in battery design.

The general architecture of carbon fiber-based batteries is illustrated in Figure 1. It consists of a carbon fiber-reinforced polymer composite, where the carbon fibers serve as both the anode (negative electrode) and the cathode (positive electrode) [15,16]. A separate interlayer or fiberglass functions as the separator, ensuring that the electrodes do not short-circuit [17]. The entire structure is embedded within a solid electrolyte, which could be a polyelectrolyte, polymer-based electrolyte, or ceramic electrolyte, depending on the specific design and performance requirements [18,19]. Here, solid electrolytes can function effectively as separators. These systems leverage the unique properties of solid electrolytes, which not only facilitate ion transport between the anode and cathode but also serve as a physical barrier. The dual functionality of solid electrolytes enhances the overall safety and performance of the battery, making them an attractive option in the development of advanced energy storage solutions [20].

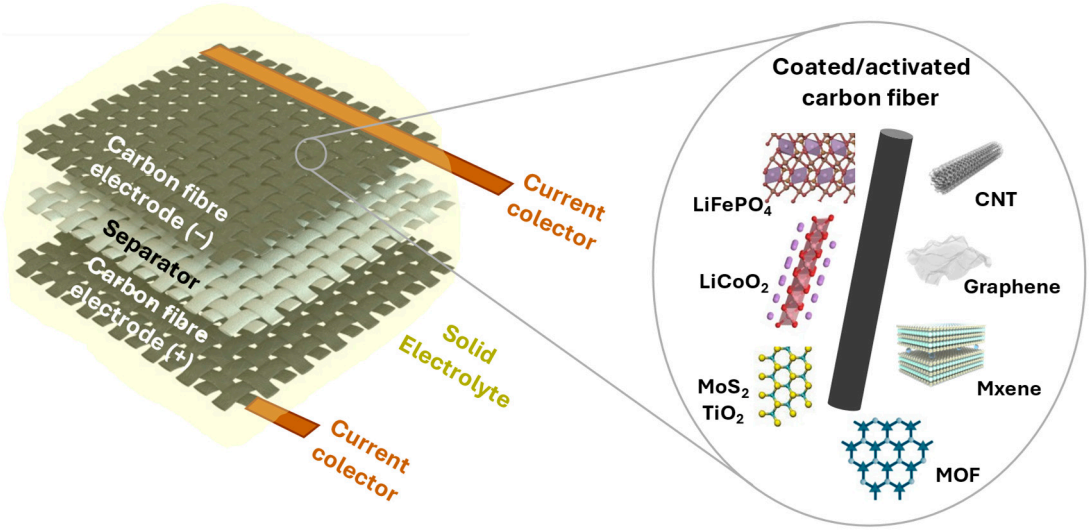

Figure 1. Schematic representation of the innovative carbon fibre-based battery architecture. The carbon fibres, integrated into a reinforced polymer composite, serve dual roles as both anode and cathode.

Electrode polarization is a key factor in the performance of carbon fiber-based batteries, affecting charge/discharge rates, energy efficiency, and lifespan [21,22]. It is influenced by internal resistance, electrode surface characteristics, and electrolyte composition. In carbon fiber systems, factors like fiber structure, porosity, and coatings impact ion transfer and reaction kinetics. Additionally, the choice of electrolyte, especially solid-state or polymer-based, can alter polarization levels. Mitigating polarization involves optimizing electrode design and choosing electrolytes that enhance ionic conductivity, leading to more efficient energy storage and longer battery life. This understanding is crucial for advancing carbon fiber-based batteries.

The scientific community has been particularly focused on leveraging the high surface area, tunable porosity, and excellent electrochemical stability of coated carbon fibers to improve the performance of batteries. One of the most significant advantages of carbon fiber-based electrodes is their potential to enhance charge/discharge rates, increase energy density, and extend the lifespan of batteries [23]. Moreover, the inherent flexibility and durability of carbon fibers open new possibilities for the development of flexible and wearable energy storage devices, which are increasingly in demand in consumer electronics and biomedical applications. For this purpose, carbon fibers are activated as cathodes or coated as anodes/cathodes with $LiFePO_4$ [24–26], $LiCoO_2$ [27,28], MoS_2 [29,30], TiO_2 [31,32], metal organic frameworks (MOFs) [33,34], Mxenes [35,36], graphene [8,37] or carbon nanotubes (CNTs) [9,38,39].

However, despite these advantages, the integration of carbon fiber into battery systems presents several challenges. Key issues include the optimization of the fiber-matrix interface

to ensure efficient electron and ion transport, the prevention of degradation mechanisms that could compromise battery performance, and the scalability of manufacturing processes for large-scale production. Addressing these challenges requires a deep understanding of the interplay among the microstructure of carbon fibers, their electrochemical behavior, and the overall battery architecture.

Various authors have made scientific reviews on structural batteries [40–42] or multifunctional composites for energy storage [43–46]. However, there are no existing studies that provide a bibliometric analysis focusing on trends and future perspectives in carbon fiber-based batteries. Thus, this study aims to provide a detailed bibliometric analysis, tracing the evolution of this research field over the past decade while highlighting key trends, emerging technologies, and critical challenges. Additionally, it explores the potential of carbon fiber to revolutionize energy storage by discussing future directions and opportunities for innovation in this rapidly growing area of research. The insights gained from this study could pave the way for significant breakthroughs in the design and application of multifunctional materials in energy storage, ultimately supporting the global transition to a cleaner and more sustainable energy future.

2. Methods

Due to the nature and breadth of the topic, the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement [47] was selected as a suitable approach to search for and identify relevant documents. Additionally, a bibliometric analysis and scientific mapping approach was followed to analyze the documents which is regarded as an appropriate and effective approach to examine such topics based on the existing literature [48]. Scopus and Web of Science (WoS) were selected as the most suitable databases due to their containing highly impactful documents and sources related to the topic, and their ability to generate data that can be used by "Bibliometrix" which was the tool used to analyze the documents. Specifically, "Bibliometrix" is an open-source R package developed to aid in the conduct of bibliometric analysis and scientific mapping studies [49].

The following query was used: (TITLE-ABS-KEY (["carbon fibre" OR "carbon fibres"]) AND TITLE-ABS-KEY (["battery" OR "batteries"]) AND TITLE-ABS-KEY (["energy" OR "storage"]) AND NOT TITLE-ABS-KEY (["supercapacitor" OR "supercapacitors" OR "fuel cell"])). All types of documents were assessed. However, only documents published in English and during 2013–2023 were considered. The specific duration was selected to explore the advancement of the field in the last decade. Data from 2024 was not included as 2024 was still ongoing when this study took place. For a study to be deemed as eligible, the following inclusion criterion was set: The study should focus on carbon fiber-based batteries and their use as a means to store energy.

When using the aforementioned query in August 2024, a total of 1014 documents (Scopus: 940 and WoS: 74) were identified. Out of these documents, 44 were duplicates and were removed. Hence, 970 documents were assessed for eligibility. After manually processing the documents, 130 documents were removed. Specifically, 17 documents were removed as they were proceedings books, 1 was removed because it was a book, 2 were removed as they were short communications and notes, 1 was removed because it was an erratum, and 109 documents were removed since they did not meet the inclusion criterion set. As a result, the document collection examined in this study consisted of 840 documents. Figure 2 presents the document processing.

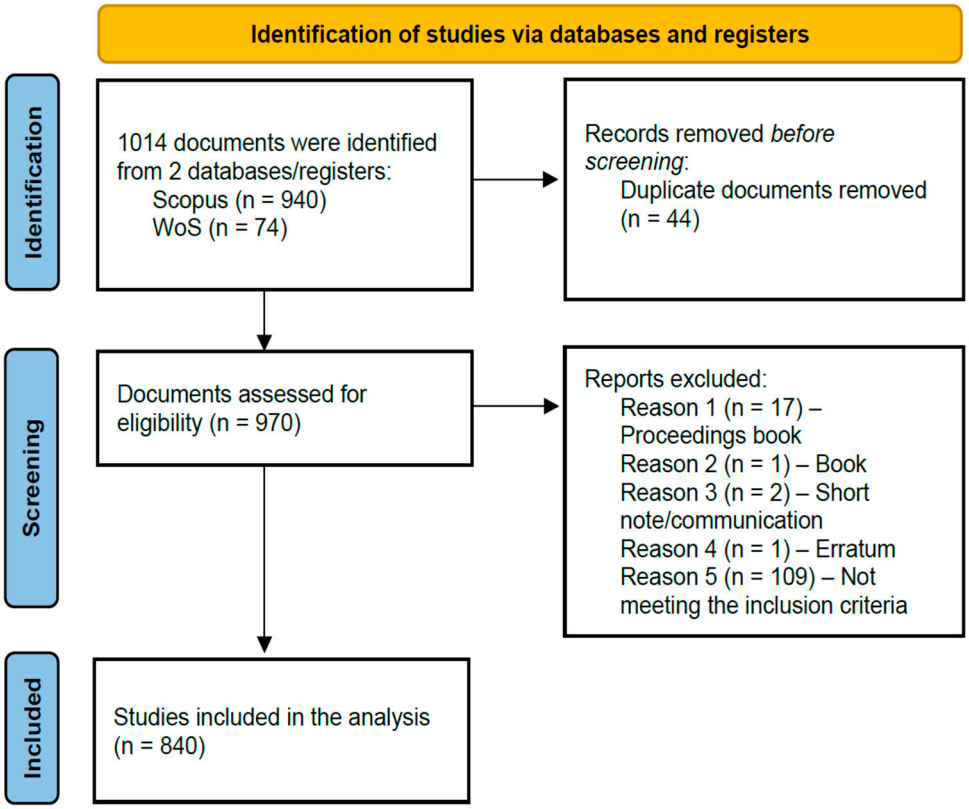

Figure 2. Comprehensive Workflow for Document Processing.

3. Results and Discussion

This section presents the information of the document collection examined and goes over different aspects of the documents. Specifically, the number of published documents and the number of citations received are examined, the sources used are explored, and the authors' affiliations and countries are looked into. Moreover, the documents are further analyzed using keywords to identify the trend topics, the conceptual structure map, the thematic map, and the evolution of the topic.

3.1. Document Collection

The information of the document collection is summarized in Table 1. Specifically, the document collection consists of 840 documents that were published during the last decade (2013–2023). The documents were published in 248 different sources and were written by 2183 authors. Within the document collection, only five documents were single-authored which further highlights the large number of co-authors per document (6.49). However, the international co-authorship rate is extremely low (1.43%) as most collaborations materialized in inter-country settings. Furthermore, the documents of the collection have an average age of 4.12 years and received 36.81 citations on average. The relatively high annual growth rate (24.08%) is in line with the increasing interest in the topic and the need to further explore it. The significant majority of documents were published in journals and in comparison, a limited number of documents were published as conference/proceedings papers. Within the documents, 4516 unique keywords plus and 2089 unique author's keywords were used to characterize and encapsulate the contents and topic of each document.

Table 1. Document collection information (2013–2023).

Description	Results	Description	Results
Main information about data		**Document types**	
Timespan	2013:2023	article	756
Sources (Journals, Books, etc)	248	book chapter	2
Documents	840	conference/proceedings paper	64
Annual Growth Rate %	24.08	review	18
Document Average Age	4.12	**Authors**	
Average Citations per Document	36.81	Authors	2183
		Authors of single-authored docs	4
Document contents		**Authors collaboration**	
Keywords Plus (ID)	4516	Single-authored docs	5
Author's Keywords (DE)	2089	Co-Authors per Doc	6.49
		International co-authorships %	1.43

3.2. Annual Published Documents and Citations

When taking into account the high annual growth rate (24.08%) and the average document age (4.12) during the 2013–2023 time period as well as the fact that most documents were published in the last five years (2019–2023) (freq. = 597 and perc. = 71.1%), the significance and recency of the topic become evident. Moreover, it is worth mentioning that a significant portion of the documents were published in the last two years (2022–2023) (freq. = 291 and perc. = 34.6%) which indicates the high interest in this topic which is expected to further increase in the future. Therefore, it comes with no surprise that most documents were published in 2023 (17.5%), followed closely by those published in 2022 (17.1%) which is a significant increase compared to the documents published in 2014 (1.9%) and 2013 (2.0%) respectively. The annual scientific production of the document collection examined is presented in Figure 3. However, when taking into account the mean total citations per document, it becomes evident that the documents published in 2013 (MeanTCperDoc = 109.47) and 2014 (MeanTCperDoc = 95.31) laid the foundations for this field of study to mature and further advance. Other impactful years were 2018 (MeanTCperDoc = 68.18) and 2016 (MeanTCperDoc = 60.89). However, it should be noted that the total number of documents published in each year and the citable years strongly influence these outcomes. Hence, it is expected that these results will change in the future. To provide a more in-depth look into the most impactful documents, the documents are further examined in document analysis section. The annual scientific production and citations are presented in detail in Table 2.

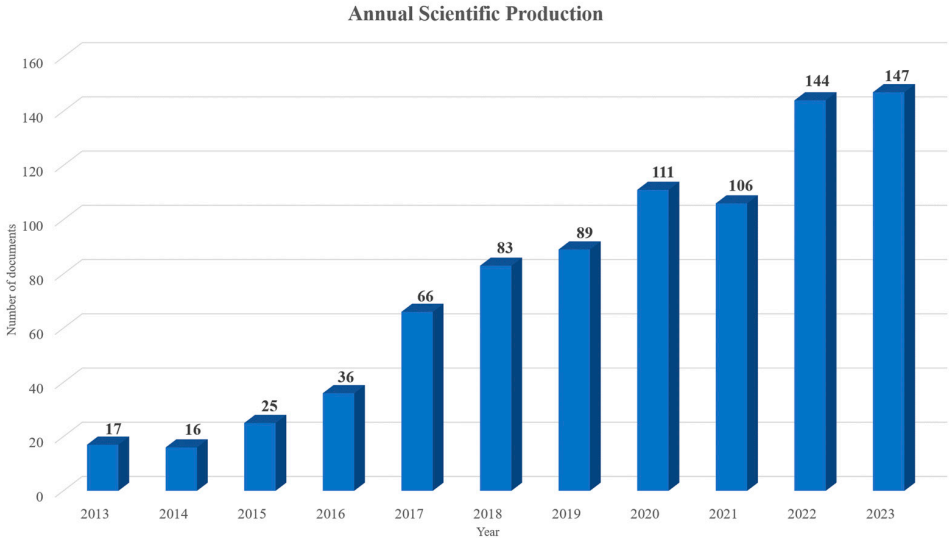

Figure 3. Annual published documents (2013–2023).

Table 2. Annual scientific production and citations (2013–2023).

Year	MeanTCperDoc	N	MeanTCperYear	CitableYears
2013	109.47	17	9.12	12
2014	95.31	16	8.66	11
2015	33.08	25	3.31	10
2016	60.89	36	6.77	9
2017	50.92	66	6.36	8
2018	68.18	83	9.74	7
2019	54.25	89	9.04	6
2020	40.95	111	8.19	5
2021	24.4	106	6.1	4
2022	16.73	144	5.58	3
2023	7.69	147	3.85	2

3.3. Sources

Of the 840 documents examined, the vast majority were published as journal articles (90.0%). To a significantly less extent, documents were published as conference/proceedings paper (7.6%) and review articles (2.1%). Only two documents (0.2%) were published as book chapters. Additionally, "ACS Applied Materials & Interfaces" (h-index: 25 and total citations: 2208), "Journal of Materials Chemistry A" (h-index: 23 and total citations: 1810), "Electrochimica Acta" (h-index: 22 and total citations: 1874), "Journal of Power Sources" (h-index: 21 and total citations: 1406), and "Electrochimica Acta" (h-index: 19 and total citations: 997) emerged as the top-5 sources when considering the h-index and total citations received. The detailed list of the most impactful sources is depicted in Table 3.

Table 3. Most impactful sources based on h-index and total citations.

Sources	h-Index	g-Index	m-Index	TC	NP	PY_Start
ACS Applied Materials & Interfaces	25	44	2.083	2208	44	2013
Journal of Materials Chemistry A	23	30	1.917	1810	30	2013
Electrochimica Acta	22	26	2.75	1874	26	2017
Journal of Power Sources	21	27	1.909	1406	27	2014
Chemical Engineering Journal	17	29	2.125	997	29	2017
Small	15	19	1.875	1012	19	2017
Advanced Functional Materials	14	15	1.273	1381	15	2014
Carbon	14	19	1.167	705	19	2013
Nano Energy	14	15	1.167	1480	15	2013

Using Bradford's law, the sources were further examined. The documents were further analyzed using clustering by coupling. Specifically, documents were set as the analysis unit, references were used as the coupling measurement and citation score was used as the impact measure. Moreover, the clustering algorithm used was Walktrap, the number of units were set to 250, and the min cluster frequency was set to 5 which are the default values suggested by the tool used in this study. Specifically, the sources were grouped into three clusters. Cluster 1 has the most impactful sources, followed by cluster 2 and cluster 3. Based on the outcomes, cluster 1 had 11 (4.4%) sources, cluster 2 had 42 (16.9%) sources, and cluster 3 had 195 (78.6%) sources. Moreover, cluster 1 had a total of 292 (34.8%) published documents, cluster 2 had 274 (32.6%) published documents, and cluster 3 also had 274 (32.6%) published documents. Table 4 presents the top-10 sources according to Bradford's law. Out of all sources, "ACS Applied Materials & Interfaces", "Electrochimica Acta", "Journal of Materials Chemistry A", "Chemical Engineering Journal", and "Journal of Alloys and Compounds" arose as the top-5 most impactful ones following Bradford's law.

Table 4. Most impactful sources based on Bradford's law.

Source	Rank	Freq	cumFreq	Cluster
ACS Applied Materials & Interfaces	1	44	44	Cluster 1
Electrochimica Acta	2	35	79	Cluster 1
Journal of Materials Chemistry A	3	30	109	Cluster 1
Chemical Engineering Journal	4	29	138	Cluster 1
Journal of Alloys and Compounds	5	28	166	Cluster 1
Journal of Power Sources	6	27	193	Cluster 1
Energy Storage Materials	7	26	219	Cluster 1
ACS Applied Energy Materials Journal	8	19	238	Cluster 1
Carbon	9	19	257	Cluster 1
Small	10	19	276	Cluster 1
Composites Science and Technology	11	16	292	Cluster 1

3.4. Affiliations

The top-10 affiliation based on the number of published documents is presented in Figure 4. More specifically, KTH Royal Institute of Technology (Sweden) (52 documents), Central South University (China) (45 documents), Hunan University (China) (44 documents), Chalmers University of Technology (Sweden) (33 documents), and Zhejiang University (China) (32 documents) arose as the top-5 affiliations that have contributed the largest number of documents to this topic. The affiliation collaboration network (Figure 5) highlights the high number of intra-country collaborations (SCP) and simultaneously, the lack of inter-country collaborations (MCP) as it becomes more evident when analyzing the country specific information in the next section.

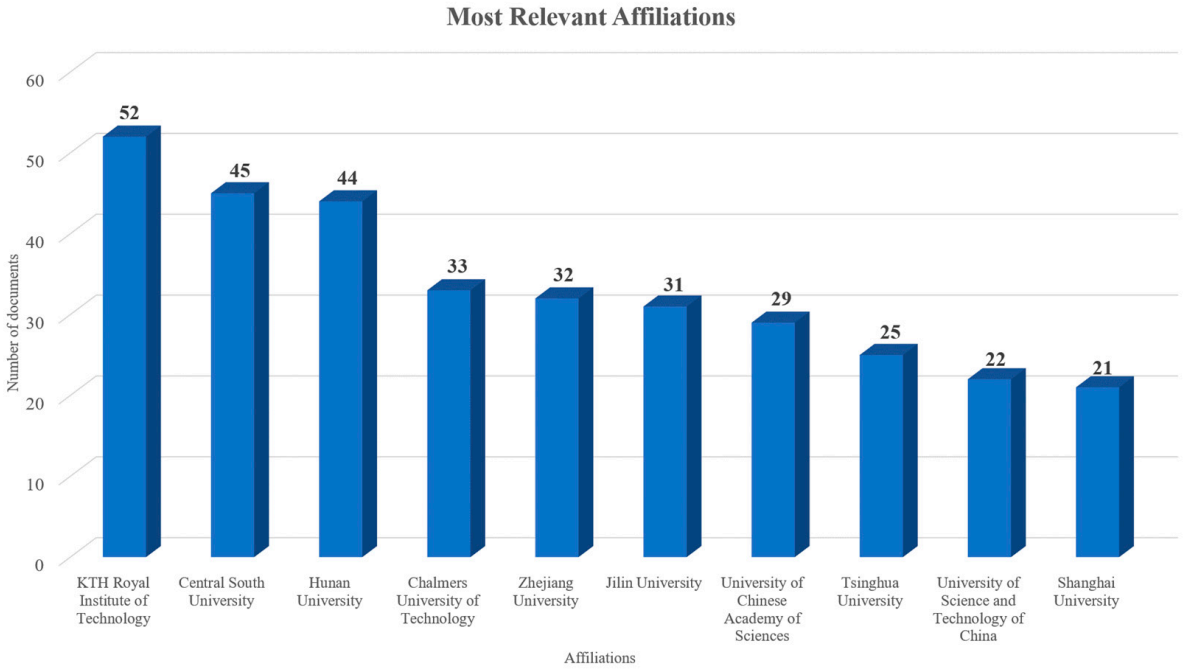

Figure 4. Top affiliations based on the number of documents published.

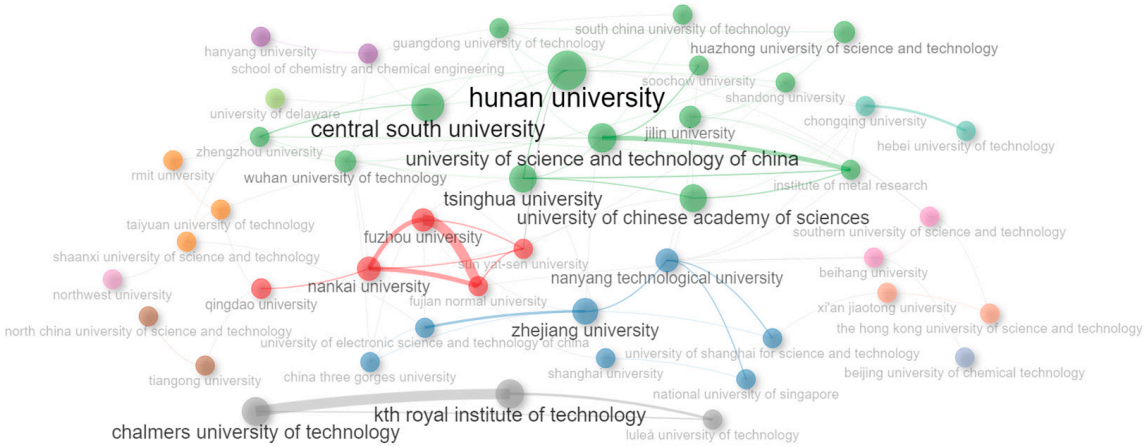

Figure 5. Global collaboration network among affiliations.

3.5. Countries

The documents of the document collection examined were written by 2183 authors from 32 countries. For each document, the country of the corresponding author was used. In the case that there was no corresponding author indicated in the document, the country of the first author was used. The top-10 countries according to the number of documents published are presented in Table 5. Based on the results, China (517 documents), the United States (70 documents), Sweden (52 documents), South Korea (37 documents), and Australia (31 documents) emerged as the top-5 countries that have contributed the largest number of relevant to the topic documents. When examining the SCP and MCP, once again, China (SCP = 515), the United States (SCP = 70), Sweden (SCP = 51), South Korea (SCP = 37), and Australia (SCP = 29) were the countries with the highest number of intra-country collaborations. When considering the low levels of inter-country collaborations and taking into account the extremely low rate of international collaborations (1.43%), the drastic need for more international collaboration to materialize to advance this field of study becomes evident. This fact becomes more obvious when examining the country collaboration network (Figure 6) and collaboration map (Figure 7) in which the limited number of international collaborations can be seen.

Table 5. Countries that published the most over time.

Country	Articles	SCP	MCP	Freq	MCP_Ratio
China	517	515	2	0.615	0.004
United States	70	70	0	0.083	0
Sweden	52	51	1	0.062	0.019
South Korea	37	37	0	0.044	0
Australia	31	29	2	0.037	0.065
India	19	19	0	0.023	0
Germany	18	17	1	0.021	0.056
Hong Kong	14	14	0	0.017	0
Singapore	12	12	0	0.014	0
Japan	10	10	0	0.012	0

Furthermore, Table 6 presents the top countries based on the total citations received. According to the findings, China (20,033 citations), the United States (2963 citations), Sweden (1694 citations), Australia (1408 citations), and South Korea (934 citations) were the top-5 countries that have received the most citations. Among the top-10 countries in terms of total citations received presented in Table 7, Georgia (ACR = 90), Czech Republic (ACR = 88), Singapore (ACR = 74.8), Hong Kong (ACR = 55.6), and Australia (ACR = 45.4) were the countries with the largest number of ACR per document.

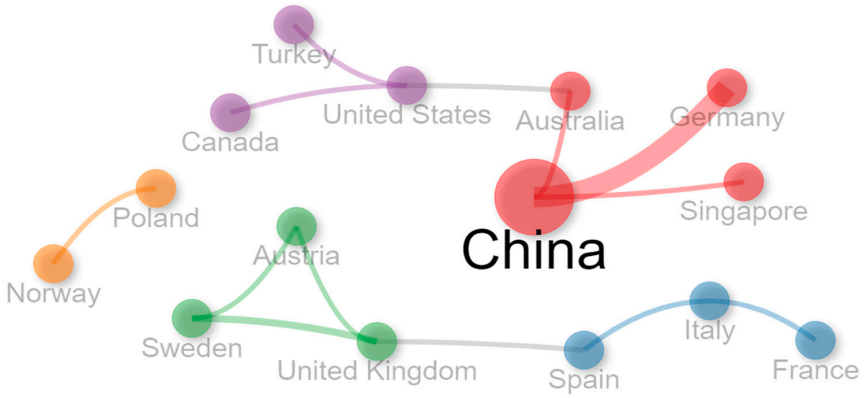

Figure 6. Country collaboration network.

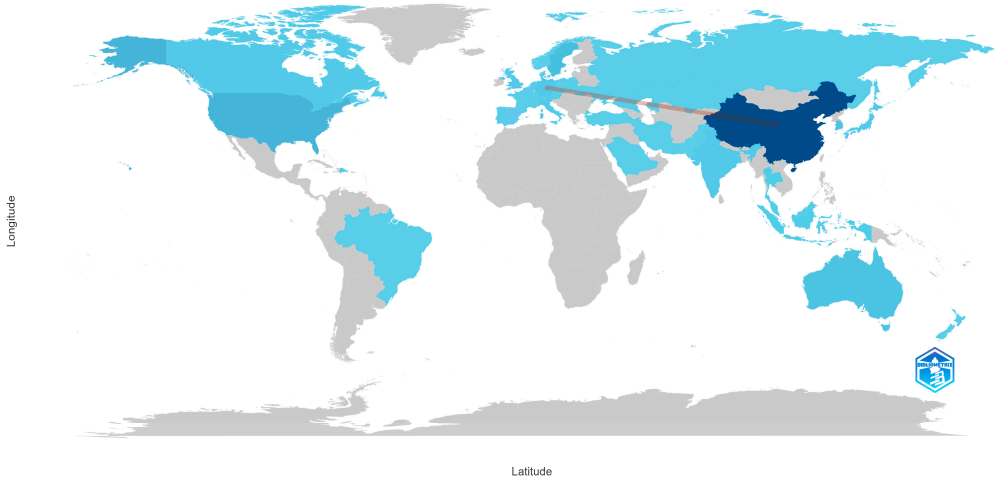

Figure 7. Country collaboration map.

Table 6. Countries that received the most citations.

Country	TC	Average Document Citations
China	20,033	38.7
United States	2963	42.3
Sweden	1694	32.6
Australia	1408	45.4
South Korea	934	25.2
Singapore	897	74.8
Hong Kong	779	55.6
Germany	396	22
India	376	19.8
Georgia	270	90

The number of total citations received was also examined to identify the most impactful countries in terms of the total number of citations the documents written by authors affiliated with an institute in this specific country received. Particularly, the United States (1752 total citations), Australia (1124 total citations), Israel (705 total citations), and China (572 total citations) were the top-4 countries which received the most citations. The list of the top-10 countries in terms of the total citations received is presented in Table 6. Additionally, when looking at the average article citations for each country, the documents written by authors in Israel received a significantly higher number of average citations per document (352.5). Documents coming from Australia (62.4) and Denmark (43.2) also showcased a high level of average citations received (ACR) per document.

Table 7. Countries that with the highest average citations received per document.

Country	TC	Average Document Citations
Georgia	270	90
Czech Republic	88	88
Singapore	897	74.8
Hong Kong	779	55.6
Australia	1408	45.4
United States	2963	42.3
China	20,033	38.7
Switzerland	37	37
Turkey	37	37
Thailand	173	34.6

3.6. Document Analysis

Table 8 presents the most impactful documents based on the global citations they have received. Based on the results, the studies of R. Zhang et al. (2018), Zhu et al. (2013), Fu et al. (2014), W. Zhang et al. (2018), and Zhong et al. (2018) emerged as the top-5 most impactful ones. Taking these outcomes into account, it can be inferred that the focus is on developing high-performance, durable electrochemical anodes by exploring various coatings on carbon fiber that incorporate nanoparticles and lithium. This is because the practical use of non-coated lithium metal anodes has been limited by challenges such as low cycling efficiency, short lifespan, and safety concerns.

Table 8. Most impactful documents based on the total number of citations received.

Document	Total Citations	Total Citations per Year	Normalized Total Citations
R. Zhang et al. (2018) [50]	622	88.86	9.12
Zhu et al. (2013) [51]	598	49.83	5.46
Fu et al. (2014) [52]	536	48.73	5.62
W. Zhang et al. (2018) [53]	462	66	6.78
Zhong et al. (2018) [54]	360	51.43	5.28
Liu et al. (2017) [55]	331	41.38	6.5
Pan et al. (2017) [56]	317	39.63	6.22
Shi et al. (2019) [57]	300	50	5.53
Wang et al. (2013) [58]	295	24.58	2.69
Huang et al. (2020) [59]	266	53.2	6.49

To better understand the scope and breadth of the topic and how it has been shaped throughout the years, keywords plus were used to further analyze the documents. Specifically, keywords plus result in more accurate and representative outcomes when compared to author's keywords (Zhang et al., 2016) and therefore, have been used in the analysis. Among the keywords plus used, "carbon fibers" (n = 560), "anodes" (n = 317), "lithium-ion batteries" (n = 288), "electrodes" (n = 179), and "lithium compounds" (n = 177) emerged as the top-5 most commonly used. Figure 8 summarizes the top-10 most frequently used keywords plus.

Based on the outcomes, the scientific community has focused on three main areas. Firstly, the most investigated is the development of anodes for lithium-ion batteries, as this area faces high global demand and presents greater challenges compared to cathodes. Anodes are subject to issues such as dendrite formation during charging [60], significant volume changes of lithium during charge and discharge, leading to crack formation [61], and potential side reactions with the electrolyte, which generate products that can degrade battery performance and reduce capacity [62]. Secondly, the development of a new generation of carbon fiber-based cathodes involves activating them with coatings of $LiFePO_4$, $LiCoO_2$, or their derivatives. Additionally, recent efforts have focused on developing cobalt-free cathodes due to the high cost and difficulty of extraction. These cobalt-free

alternatives offer more sustainable solutions for large-scale production while maintaining comparable performance metrics [63,64]. The final area of focus is the development of solid electrolytes, which must simultaneously achieve high ionic conductivity and elevated mechanical properties to guarantee the multifunctionality of the composite. However, it has been demonstrated that these two properties are often in conflict [18,65].

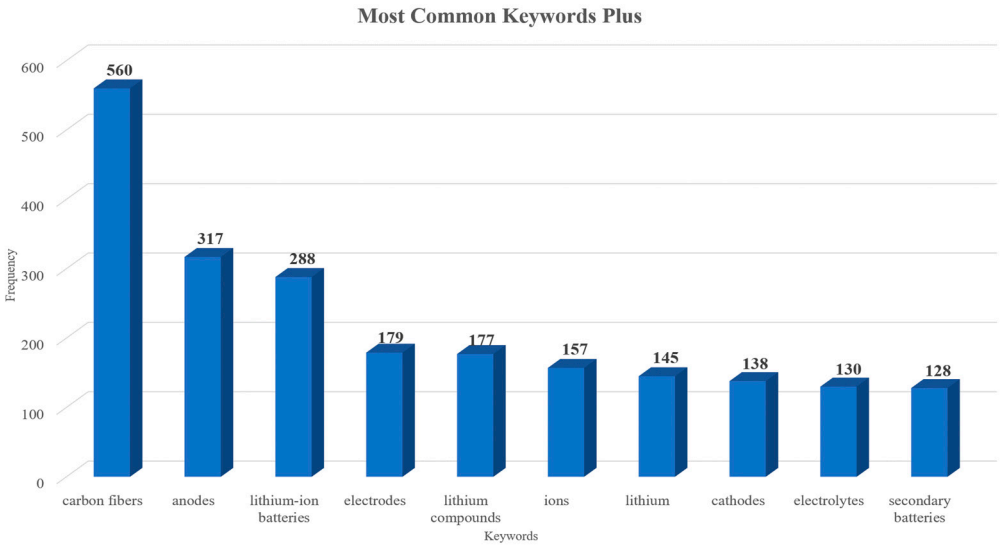

Figure 8. Most frequent keywords plus.

The keyword co-occurrence network presented in Figure 9 revealed three main areas. Specifically, the central and most prominent cluster is focused on 'carbon fibers', which is heavily linked to "lithium-ion batteries" and "anodes". This central cluster indicates a strong relationship between these terms within the research or context provided. Surrounding this main cluster are two other significant areas: one that includes terms like "vanadium", "flow batteries", and "energy storage" suggesting a focus on alternative battery technologies and energy storage solutions. Here, vanadium-based energy storage, particularly in vanadium redox flow batteries, has shown promise for large-scale applications due to its high energy capacity and long cycle life. Flow batteries, in general, provide a scalable solution for renewable energy integration, as they allow for independent scaling of power and energy capacities, making them ideal for grid-level storage. The other area includes terms such as "solid electrolytes", "redox reactions", and "electrochemical performance", pointing towards research in advanced battery materials and their performance. Figure 10 presents the relationships among the top countries, keywords, and sources.

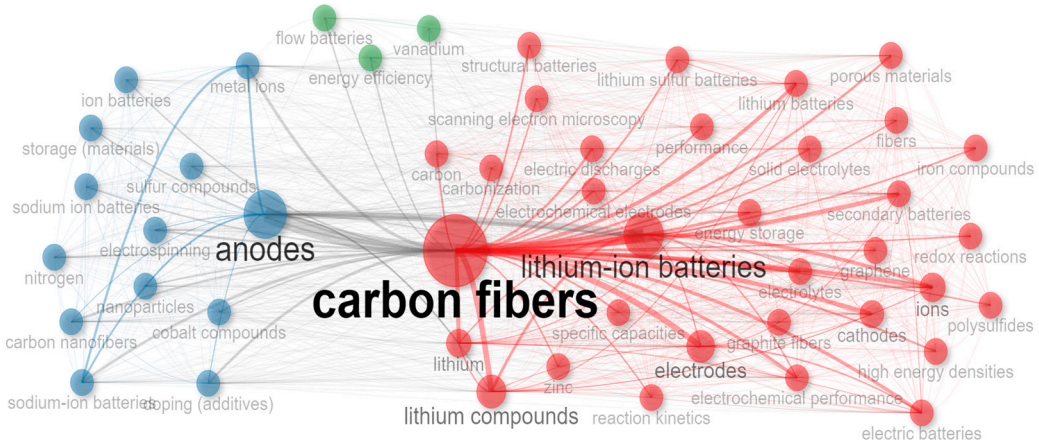

Figure 9. Keywords plus co-occurrence network.

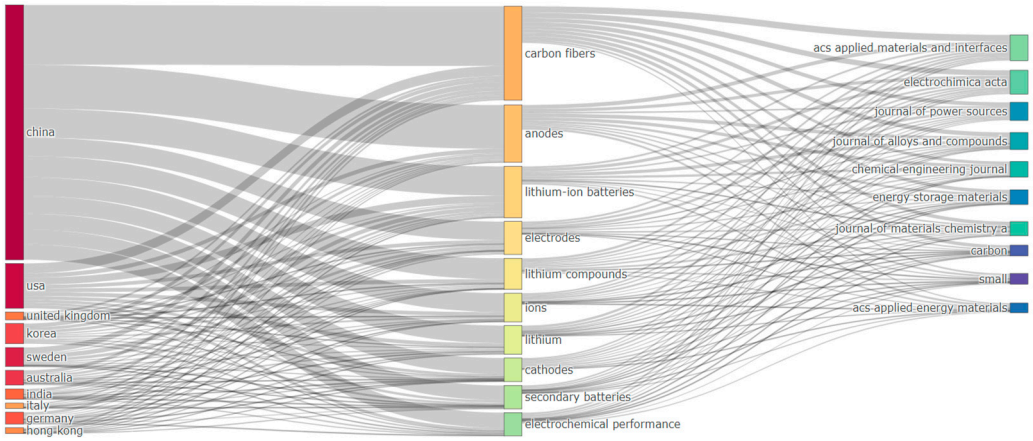

Figure 10. Countries, keywords, and sources relationship.

Furthermore, Figure 11 displays the most popular topics and their progression over the years based on keywords plus. According to the outcomes, the current focus in the development of carbon fiber-based batteries is on creating low-cost batteries utilizing sodium ions, with an optimized structural design. Moreover, we can see the importance of scanning electron microscopy in the development of these devices, as it is a critical machine to master their operation and optimization.

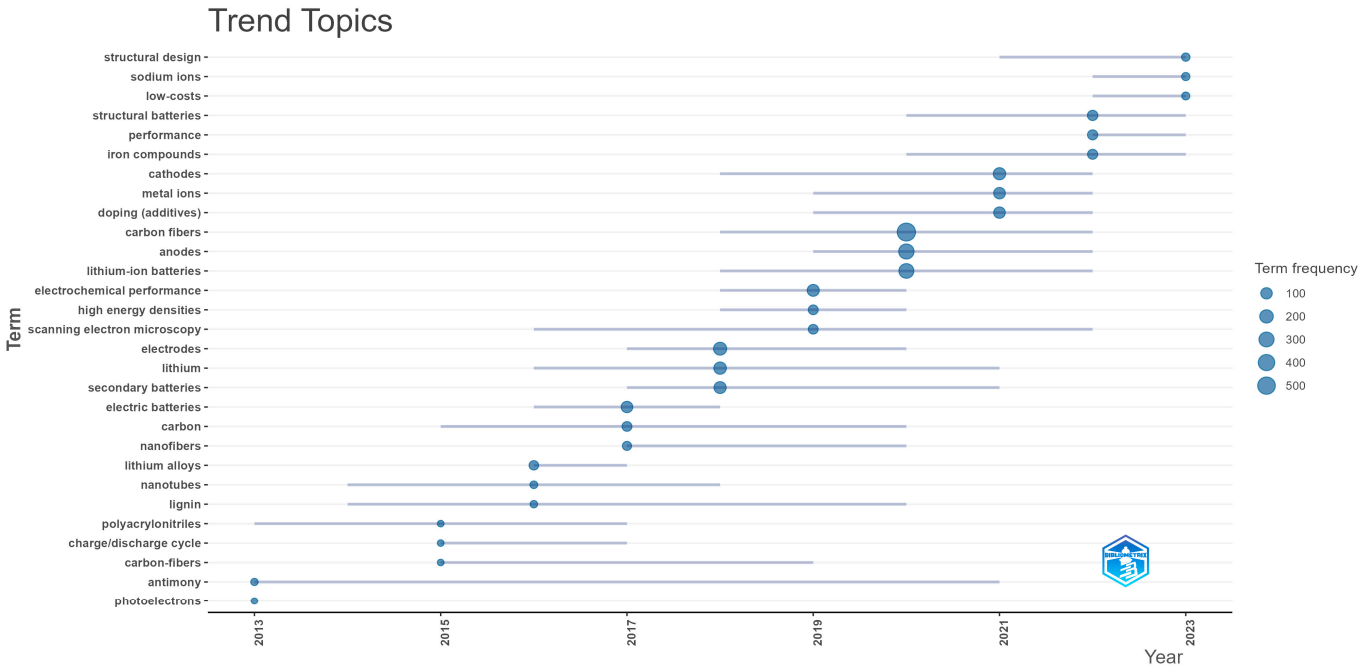

Figure 11. Trend topics based on keywords plus.

When examining the conceptual structure map of the topic, four main dimensions arose as it can be seen in Figure 12. According to the results, the dimensions were related to: (i) carbon fibers, anodes, and lithium, (ii) carbon fibers, anodes, and metal ions, (iii) carbon fibers, lithium-ion batteries, and anodes, and (iv) carbon fibers, lithium-ion batteries, and electrodes. Based on the dimensions that emerged, it can be inferred that carbon fibers play a central role in the development of advanced battery technologies. The repeated association of carbon fibers with anodes, lithium, and lithium-ion batteries highlights their importance in enhancing the performance and efficiency of these components. Additionally, the inclusion of metal ions and electrodes in the dimensions suggests a focus on optimiz-

ing the materials and structures used in batteries to improve their overall functionality and longevity.

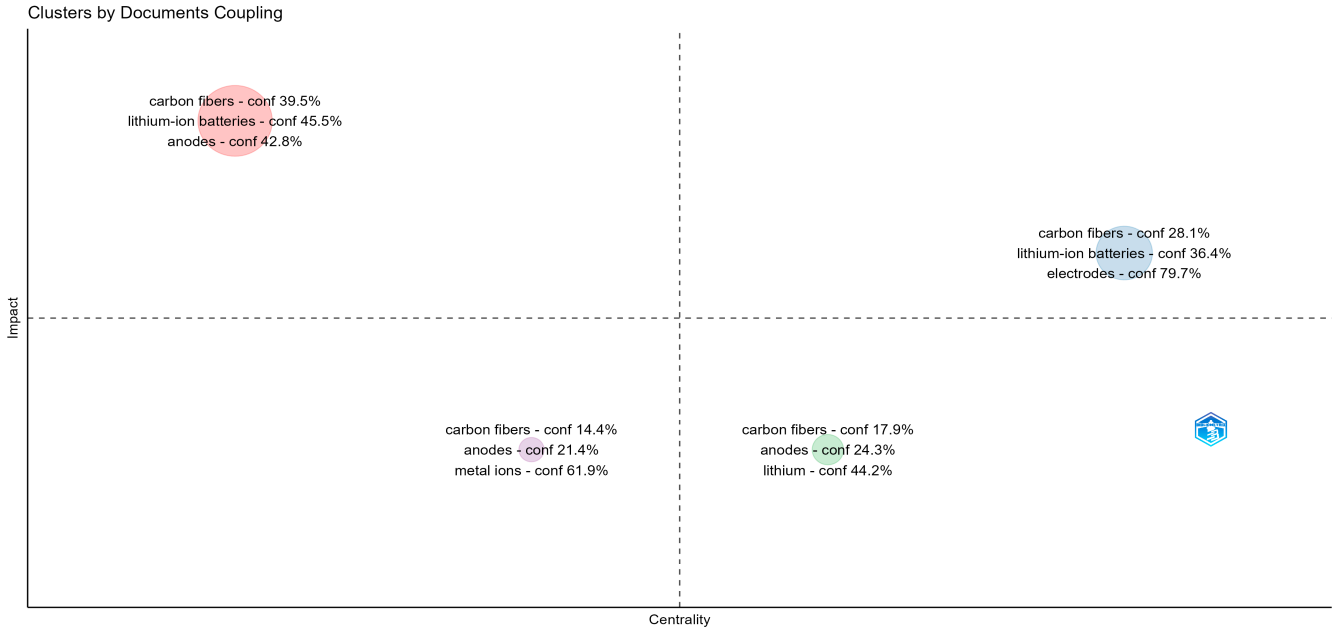

Figure 12. Conceptual structure map.

The thematic map of the topic which is displayed in Figure 13 presents the six themes that emerged. The themes are separated into basic themes, emerging or declining themes, niche themes, and motor themes. Two basic themes arose that were related to: (i) lithium compounds, electrodes, and lithium and (ii) electrochemical electrodes, redox reactions, and cyclic voltammetry. One emerging or declining theme arose which was associated with (i) energy efficiency, flow batteries, and vanadium. Two niche themes were identified that were related to (i) structural batteries, multifunctional composites, and polyelectrolytes and (ii) zinc, oxygen, and electrolytic reduction. The motor theme that arose was associated with (i) carbon fibers, anodes, and lithium-ion batteries. Based on these outcomes, it can be noted that the development of carbon fiber-based batteries is a central focus, particularly in enhancing the performance and efficiency of lithium-ion batteries. The emphasis on electrochemical electrodes and redox reactions highlights the importance of understanding and optimizing the fundamental processes within these batteries. Additionally, the exploration of structural batteries and multifunctional composites indicates a trend toward integrating multiple functionalities into battery materials –structural and energy storage functions especially–leading to more versatile and efficient energy storage solutions.

The thematic evolution of the topic is presented in Figure 14 in five time periods. The first time period (2013–2015) reveals that the focus was primarily on “anode”, “carbon fibres”, “energy storage”, and “mechanical properties”. These themes indicate an early emphasis on understanding and improving the fundamental components and properties of energy storage systems. As we move to the second time period (2016–2017), the themes evolve to include “cathodes”, “carbon fibres” and “energy efficiency”, reflecting a shift towards optimizing both the anode and cathode materials and improving the overall efficiency of energy storage devices. In the third time period (2018–2019), the focus expands to “carbon fibres”, “anodes”, and “composite materials” suggesting advancements in integrating carbon fibres into composite materials to enhance the performance and durability of batteries. The fourth time period (2020–2021) shows a continued emphasis on “carbon fibres”, “anodes”, and “energy storage” indicating ongoing research into improving these critical components. Additionally, “structural batteries” and “carbon nanofibers” emerge as significant themes, highlighting innovations in battery design and materials. Finally, in the

fifth time period (2022–2023), the themes include "carbon fibres," "anodes", and "lithium-ion batteries," demonstrating a mature focus on integrating carbon fibres into lithium-ion batteries to enhance their performance. The emergence of "energy efficiency" and "structural batteries" as consistent themes throughout the periods underscores the importance of these areas in the ongoing development of advanced energy storage solutions.

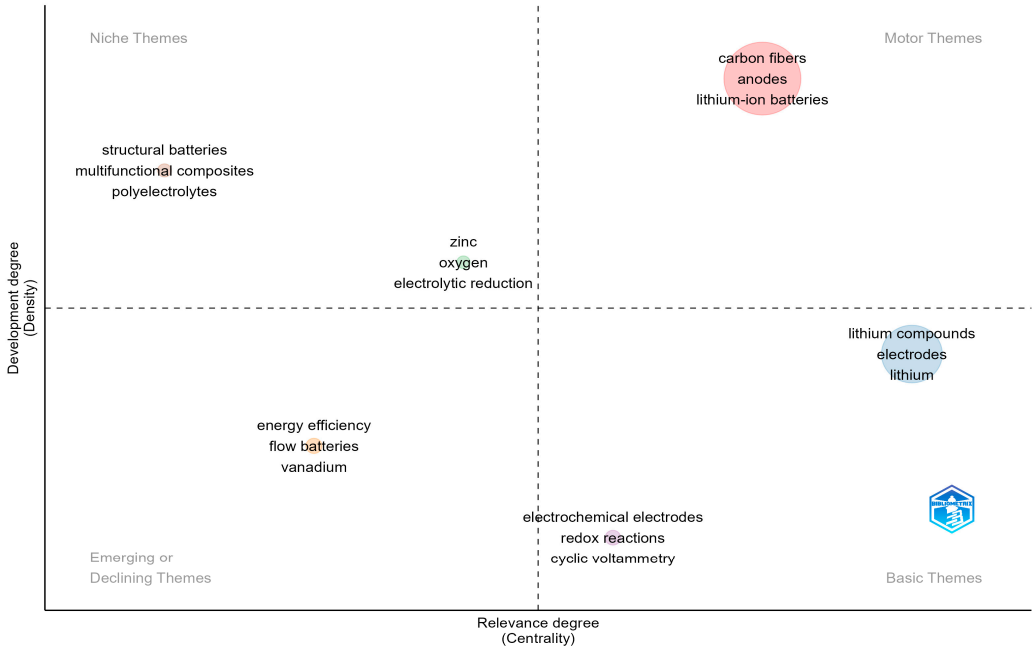

Figure 13. Thematic map of the topic.

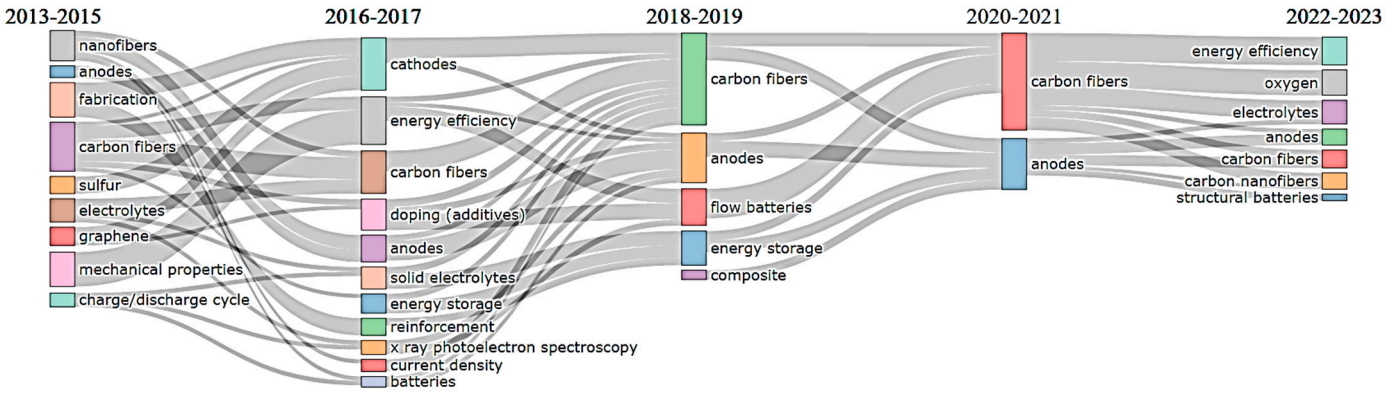

Figure 14. Thematic evolution of the topic.

Considering the bibliometric analyses of the paper, Figure 15 presents key trends and future perspectives in energy storage technologies based on carbon fiber-based batteries. The bibliometric analysis highlights three primary areas: the development of carbon fiber-based anodes for lithium-ion batteries, advancements in next-generation carbon fiber-based cathodes, and progress in solid electrolytes. Each domain faces significant challenges, such as dendrite formation and volume expansion in anodes, as well as the urgent need for cobalt-free alternatives in cathodes due to the high costs and extraction difficulties associated with cobalt. Efforts in solid electrolytes focus on balancing high ionic conductivity with strong mechanical properties to ensure the multifunctionality of these composite materials. Moreover, gel-based electrolytes, due to their semi-solid nature, help to reduce electrode polarization and maintain stable performance under high charge/discharge rates, making them highly suitable for demanding energy storage applications. Additionally, the geographical distribution of research contributions, with

leading countries showing high citation impacts, although international collaboration remains limited. This suggests that while some nations dominate high-impact research, global collaboration needs to be strengthened to accelerate progress in this field.

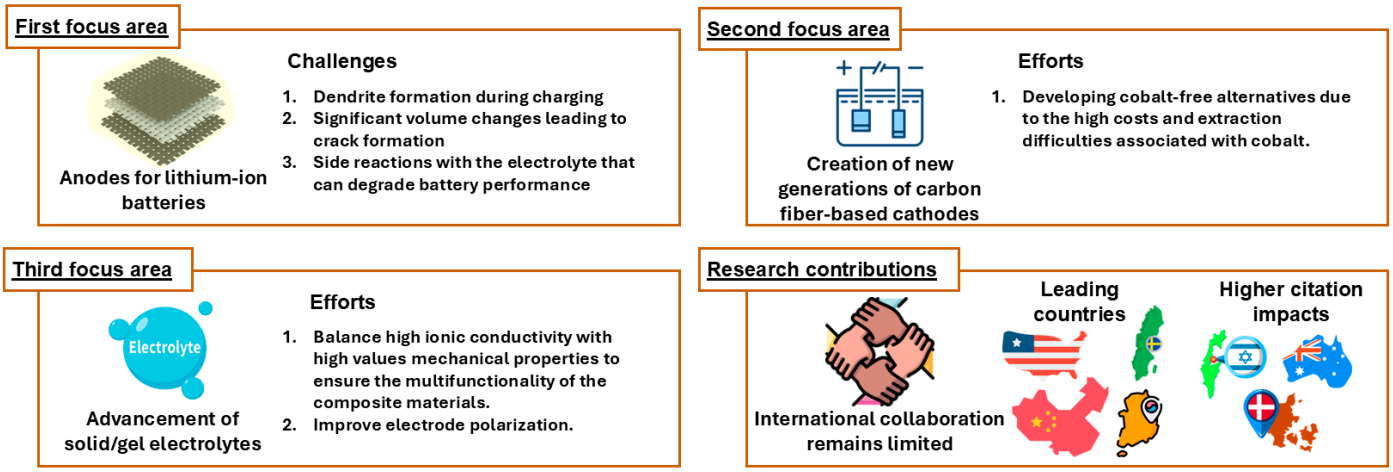

Figure 15. Key trends and future perspectives in energy storage technologies based on carbon fi-ber-based batteries.

4. Conclusions

Carbon fiber-based batteries are poised to play a transformative role in the pursuit of more sustainable energy solutions. Their unique ability to merge structural functionality with energy storage not only offers significant weight reduction and efficiency gains but also opens up new avenues for innovation across various industries. By integrating carbon fibers into battery systems, particularly as anodes, many of the critical challenges in battery performance can be addressed more effectively.

Recent research has primarily focused on three main areas within the development of carbon fiber-based batteries. The most investigated area is the development of anodes for lithium-ion batteries, driven by the high global demand and the significant challenges these anodes present, such as dendrite formation during charging, significant volume changes leading to crack formation, and side reactions with the electrolyte that can degrade battery performance.

Analysis of the research contributions reveals that China, the United States, Sweden, South Korea, and Australia are leading countries in this field, with China significantly ahead in both publication volume and intra-country collaborations. Despite this fact, international collaboration remains limited, underscoring the need for increased global cooperation. Notably, countries such as Israel, Australia, and Denmark exhibit higher citation impacts, reflecting the high quality and influence of their research.

Carbon fiber-based batteries are still in a developmental stage, with substantial research needed to realize their full potential. Future research directions should prioritize optimizing fiber-matrix interfaces to enhance electron and ion transport, scaling manufacturing processes for broader application, and developing standardized protocols to ensure consistency and reliability. Increased international collaboration will be vital in accelerating technological progress and addressing existing challenges. As the field matures, carbon fiber-based batteries hold significant promise for advancing sustainable energy systems and contributing to a decarbonized future.

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