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Review article

Visualized analysis on thermal runaway related research trends for lithium-ion batteries: A bibliometric study

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ABSTRACT

It is well known that lithium-ion batteries(LIBs) plays an important role in the energy storage space. This bibliometric study presents a visualized analysis of research trends related to lithium-ion batteries thermal runaway (LIBsTR) from 1996 to 2024. The annual publication trend shows exponential growth, transitioning from a niche concern to a mainstream priority in battery science. China leads in research output, followed by the United States, while European nations contribute high-quality but fragmented work. Chinese academic institutions are highly productive in this field. Co-authorship analysis reveals a centralized research ecosystem dominated by Chinese teams, with emerging open-collaboration models. The *Journal of Energy Storage* and the *Journal of Power Sources* are among the most productive journals, and the latter has the highest citation influence. Citation analysis indicates that top-cited papers have significantly impacted the field, with Chinese-affiliated authors becoming prominent post-2015. Keyword analysis shows that "thermal runaway," "lithium-ion battery," and "safety" are core topics. Four keyword clusters identify different research focuses, including battery components, thermal management, battery state diagnosis, and thermal runaway mechanisms. The research evolution has shifted from basic understanding to practical applications. Future research should focus on data-driven methods, early-warning systems, battery thermal management, and the development of high-power and high-energy-density battery safety technologies. However, this study has limitations, such as relying solely on the WoS database and potential tool-related restrictions.

1. Introduction

LIBs have emerged as a cornerstone in the contemporary energy storage landscape, revolutionizing various sectors such as electric vehicles (EVs), portable electronics, and large-scale energy storage systems [1]. Their high energy density, long cycle life, and relatively low self-discharge rate make them the preferred choice for many applications [2–5]. For instance, in the automotive industry, the transition from internal combustion engines to electric vehicles is largely enabled by the continuous improvement of LIB technology [6]. In the field of renewable energy, LIBs are used to store excess energy generated from solar and wind sources, ensuring a stable and reliable power supply [7].

However, the widespread use of LIBs is accompanied by significant safety concerns, among which thermal runaway (TR) is one of the most critical issues [8–10]. The thermal hazards associated with LIBs have drawn public attention to the safety risks associated with LIBs, particularly in recent years due to the rising demand for LIBs in the electric mobility market, primarily driven by the increasing adoption of electric vehicles [11,12].

Thermal runaway refers to a cascade of exothermic reactions that can occur in lithium battery under certain conditions, leading to severe overheating, gas generation, and potentially catastrophic events such as explosions and fires [13,14]. Thermal runaway incidents can also occur in LIBs when subjected to abusive conditions, including overcharging [15–19], short circuits [20], penetration [8,21–23], overheating [24], and immersion in seawater [25,26]. Thermal runaway occurs when the internal temperature of LIBs rises uncontrollably, leading to the release of flammable electrolytes, rapid self-heating, and in extreme cases,

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violent cell rupture and combustion. The consequences of thermal runaway can range from safety hazards to significant economic losses and environmental damage [25].

To address these safety concerns, extensive research has been conducted on LIBsTR in recent decades. Understanding the mechanisms, prevention, and mitigation strategies of LIBsTR is crucial for enhancing the safety and reliability of LIBs [27]. Research efforts have covered various aspects, including the chemical reactions during thermal runaway, the influence of battery design and materials on thermal stability, and the development of thermal management systems [28].

Bibliometric analysis, a quantitative approach to mapping scientific knowledge, offers a powerful tool to address this gap [29–31]. By analyzing publication trends, author/institutional collaborations, keyword co-occurrence, and citation networks, bibliometrics can reveal hidden patterns, identify research frontiers, and forecast future directions [32,33]. Bibliometric methods, as a quantitative analysis technique, are utilized to determine the current status and deficiencies in a particular field [34–38]. Numerous studies in the literature have applied bibliometrics to diverse topics, such as construction safety research [39], safety and security research [40], automotive industry supply chains [41], smart factory [42]. Furthermore, bibliometric tools have been extensively utilized in environmental and ecological fields, including digital learning environments [43], human and environment [44], and area ecological research [45].

Although there have been some studies on the research trends of LIBs in general, few have specifically focused on the research trends related to LIBsTR through a comprehensive bibliometric analysis. This study aims to fill this gap by presenting a visualized analysis of the research trends related to LIBsTR from 1996 to 2024 by utilizing tools such as VOSviewer, CiteSpace, and the Web of Science (WoS) database. We will analyze the annual publication trend, geographical distribution of research, collaboration patterns, influential journals, citation characteristics, and keyword clusters. Based on these analyses, we will also provide insights into the future research directions in this field.

The rest of this paper is organized as follows. Section 2 describes the data sources and methods used in this bibliometric study. Section 3 presents the results of the analysis, including annual publication trends, geographical distribution, co-authorship analysis, journal analysis, citation analysis, and keyword analysis. Section 4 discusses the research evolution, future research directions and concludes the paper.

2. Methodology

2.1. Data source

The information and data utilized in this scientific study were procured from the Core Collection database of WoS. Reliable data is essential to support informational measurement studies [46,47]. The WoS database is a globally recognized and scientifically credible platform for disseminating research, extensively employed by scholars worldwide [48,49]. Additionally, WOS serves as the predominant tool for comprehensive citation searches and bibliometric analysis [50,51].

The research was completed on October 1, 2025. The publications are collected through the topic research with the following retrieval formula (TS = ("lithium-ion batter*" OR "Lithium ion batter*" OR "Li ion batter*" OR "Li-ion batter*" OR "lithium-ion cell*" OR "Lithium ion cell*" OR "Li ion cell*" OR "Li-ion cell*") AND TS = ("Thermal runaway" OR "Thermal-runaway"). Since the first paper on LIBs thermal runaway was published in 1996, the timespan was set from 1996 to 01-01 to 2024-12-31. Besides, this search also encompassed other types of documents in WoS. As a result, a total of 3328 papers are obtained.

2.2. Bibliometric analysis

Bibliometric analysis methods, which apply mathematical and statistical techniques to quantitatively assess academic literature, are commonly used across a variety of fields [29]. VOSviewer and CiteSpace are both bibliometric instrument that utilizes data mining techniques to lead the sample literature data into software and subsequently constructs a knowledge map [34,48]. It has the capability to illustrate the overall attributes of this domain, leveraging the distinctive benefits of cluster analysis [26]. VOSviewer provides the benefit of graphically depicting knowledge entities found in the literature and boasts strong visualization features, making it appropriate for the examination of large-scale datasets [52]. CiteSpace offers a clearer network visualization to represent the knowledge structure and evolution of research, making it a useful and efficient tool for analyzing the structure and dynamics of co-citation networks and clusters [53]. The methodology and process adopted are depicted in Fig.1.

To systematically characterize the LIBsTR field, the following dimensions were analyzed: collaboration network analysis was conducted using VOSviewer 1.6.20 to map author/institution collaboration networks and identify core research teams as well as cross-regional collaboration patterns. Journal co-citation analysis employed VOSviewer 1.6.20 to explore the core journal cluster and their interdisciplinary connections. Keyword analysis combined VOSviewer 1.6.20 (co-occurrence clustering) and CiteSpace 6.4.R1 (burst detection) to identify research hotspots and frontiers. Citation analysis used VOSviewer 1.6.20 to extract top-cited papers and citation paths, clarifying foundational studies and their influence on subsequent research.

3. Results and discussion

3.1. Annual publication trend

The annual volume of published works can act as a reliable indicator to reflect the evolutionary path of a specific research area over time [54]. Through a comprehensive bibliometric analysis, it is evident that there has been a remarkable exponential growth in research on LIBsTR over the past three decades. As shown in Fig. 2, the annual publication count exhibits distinct development phases, which are in line with the technological adoption curve of LIBs in energy storage systems [55,56].

During the initial stage from 1996 to 2009, the research output was consistently at a low level, with an average of less than 5 publications per year. This stagnant period can be attributed to the early stages of LIBs commercialization and the limited awareness of thermal safety issues. At this time, the technology was still in its infancy, and the potential risks associated with thermal runaway had not yet attracted significant scientific attention.

The first significant upsurge in research occurred between 2010 and 2016. The number of annual publications increased from 11 to 57 papers, representing a Compound Annual Growth Rate (CAGR) of 32.6 %. This growth coincided with the global penetration of the electric vehicle market and some early safety incidents that caught the attention of the scientific community [57]. The expansion of the electric vehicle market led to a greater demand for battery safety, prompting researchers to focus more on thermal runaway issues.

A real turning point appeared after 2017. The annual output soared from 88 papers in 2017 to 672 in 2023, with a CAGR of 39.8 %. This rapid growth phase is closely related to several critical industry developments: 1) The large-scale deployment of grid-scale battery storage systems. As these systems store vast amounts of energy, the potential consequences of thermal runaway are more severe, thus increasing the need for relevant research [58]. 2) High-profile safety failures in consumer electronics and electric vehicles. These incidents not only posed risks to users but also damaged the reputation of the battery industry, driving researchers to find solutions [59]. 3) Regulatory pressures for enhanced safety standards. Governments and regulatory bodies around the world have introduced more stringent safety regulations for batteries, which has further spurred research in this area [60]. Notably, the number of publications nearly tripled from 2019 (177) to 2022 (484), possibly due to the urgent safety requirements of emerging high-nickel

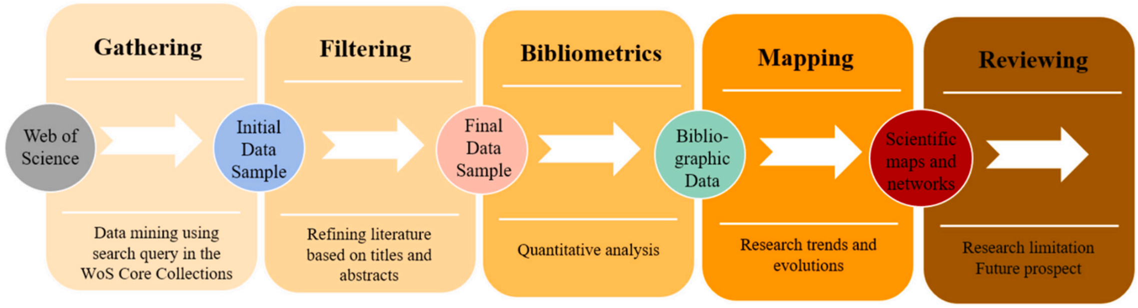

Fig. 1. The used research procedure and method.

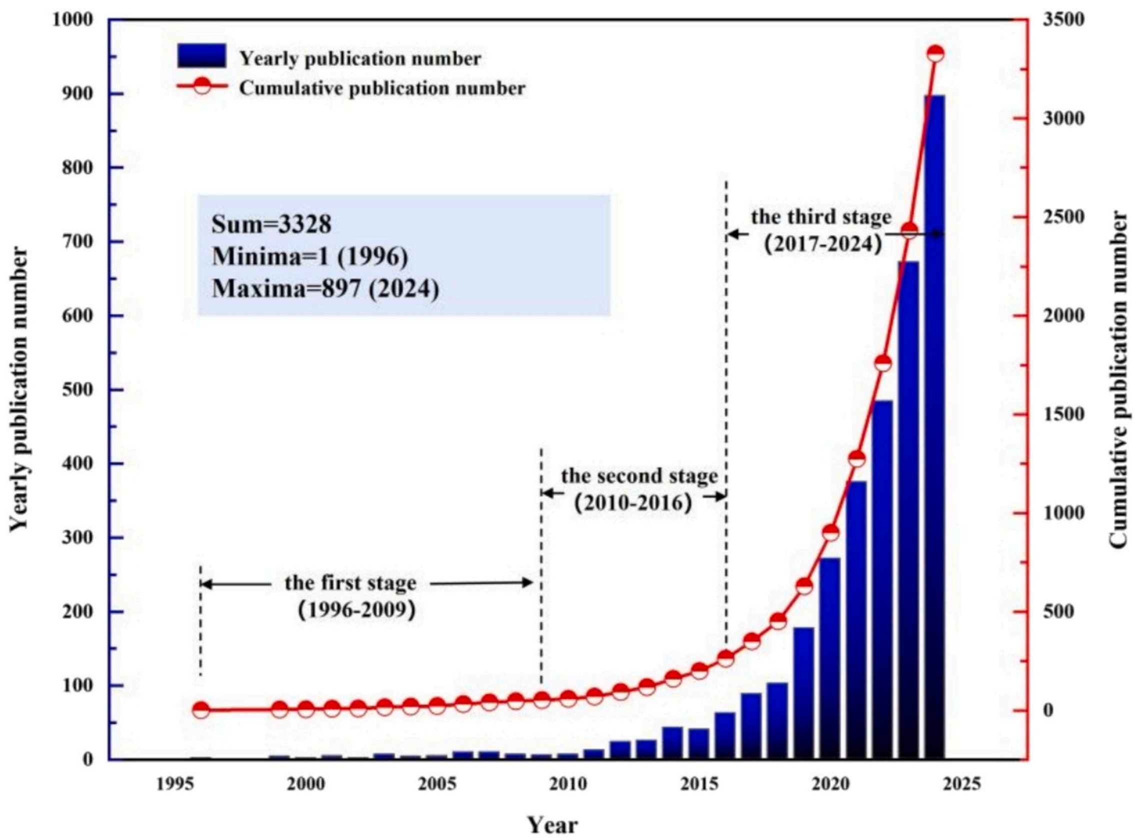

Fig. 2. The yearly publication number and cumulative number of LIBsTR.

and silicon anode chemistries. These new chemistries offer higher energy densities but also bring new thermal safety challenges [61].

The data for 2024 (897 publications) indicates that the growth momentum is still being maintained. This continuous upward trend shows that research on thermal runaway has evolved from a niche safety concern to a mainstream priority in battery science. The time it takes for the number of publications to double has significantly decreased from 8.5 years (2000–2008) to only 2.3 years (2020−2023), which reflects the intensified global research efforts to tackle the safety challenges in next-generation battery systems.

3.2. Geographical distribution of publications

The bibliometric analysis reveals substantial disparities in research contributions and influence among different countries, with certain regions clearly dominating the field of thermal runaway studies for LIBs [62–65]. Table 1, Fig.3 and Fig.4 present the global distribution of publications, citations, and collaborative networks, which can be classified into three distinct tiers of research engagement.

In Fig.3, China emerges as the undisputed leader, contributing 1967 documents (59.1 % of total publications) with 88,880 citations and the strongest international collaboration network (TLS = 419). This aligns with its strategic focus on LIB manufacturing and EV industry development, supported by national policies like the “New Energy Vehicle Industry Development Plan”. The United States ranks second in both publications (649) and citations (44,575), though its collaboration intensity (TLS = 283) trails China’s, reflecting its emphasis on domestic research ecosystems through institutions like Argonne National Laboratory and industrial partnerships with Tesla and GM.

European nations exhibit fragmented but quality-driven outputs. England leads with 217 publications and the highest continental collaboration (TLS =187), driven by Faraday Institution initiatives. Germany(171 publications) and Sweden (39 publications) demonstrate citation efficiency, achieving 35.5 and 117.4 citations per document, respectively, reflecting specialized expertise in thermal modeling and safety standardization. France and Netherlands show niche strengths in

Table 1
Countries/territories publishing paper in thermal runaway of LIBs (TOP 20).

Countries/ territories	Documents	Citations	TLS	APY	AC
China	1967	88,880	419	2022.16	46.41
USA	649	44,575	283	2019.81	68.68
England	217	12,714	187	2021.52	58.59
Germany	171	6071	97	2021.27	35.50
South Korea	168	7354	67	2020.75	43.77
India	129	4797	66	2022.21	37.19
Japan	83	2458	31	2017.89	29.61
France	71	5026	71	2020.71	65.27
Canada	66	4458	74	2020.08	67.55
Australia	61	4194	77	2021.57	68.75
Italy	46	757	22	2021.48	16.46
Sweden	39	4579	43	2020.92	117.41
Spain	35	685	15	2022.46	19.57
Saudi Arabia	27	1881	55	2022.11	69.67
Singapore	24	1601	24	2021.79	66.71
Austria	23	1862	5	2020.57	80.96
Malaysia	22	1183	39	2021.68	53.77
Russia	19	407	1	2021.89	21.42
Netherlands	17	830	22	2021.53	48.82
Turkiye	16	352	17	2023.63	22.00

Note: TLS = Total link strength, APY = Average publication year, AC = Average citations.

gas venting analysis, as evidenced by high-impact studies on CO/H_2 detection during thermal runaway.

South Korea (168 publications) and Japan (83 publications) underperform relative to their LIBs manufacturing capacities, suggesting industry-academia knowledge silos. India (129 publications) and Saudi Arabia (27 publications) show rapid growth (2020–2024 CAGR>45 %), leveraging low-cost simulation methods and oil-to-renewables transition investments. Russia(19 publications) and Iran (13 publications) exhibit minimal global integration (TLS ≤ 12), highlighting geopolitical barriers to international collaboration.

3.3. Institutional distribution analysis

The analysis of institution distribution can provide information on the most prolific organizations and group that are specialized in a certain domain within the discipline [66,67]. The research on LIBsTR is characterized by a concentrated output from Chinese academic institutions, while specialized laboratories around the world are also making emerging contributions. As depicted in Fig. 5 and Table 2, the top 15 institutions contribute 38.7 % of the total publications, and are predominantly China's "Double First-Class" universities. Fig. 5 presents the network of organizations and their inter-departmental relationships, where each circle symbolizes an organization. The minimum number of documents for an organization is set at 5, and the minimum number of citations is set at 1.

Tsinghua University leads globally with 301 publications, accounting for 6.2 % of the total output, 27,225 citations, and the strongest collaborative network (TLS = 419). Its research primarily centers on the multi-physics modeling of thermal propagation, which is supported by national electric vehicle (EV) safety standardization projects [68]. This kind of research is crucial for establishing comprehensive safety standards in the EV industry, as it provides a theoretical basis for predicting and preventing thermal runaway in real-world scenarios. University of Science and Technology of China (USTC) ranks second with 259 documents. However, compared to Tsinghua (AC = 90.45), it has a lower citation impact (AC = 69.49). This difference reflects USTC's emphasis on fundamental electrolyte decomposition mechanisms rather than applied solutions. Understanding these fundamental mechanisms is the cornerstone for developing new battery chemistries and materials to enhance battery safety at the molecular level. Beijing Institute of Technology demonstrates unique strength in military-grade battery safety, with 208 TLS indicating intensive collaborations with defense industries on thermal runaway suppression coatings.

Nanjing Tech University(APY = 2022.59) and University of Shanghai for Science and Technology(TLS = 120) prioritize thermal management system innovations for commercial EVs, evidenced by recent patents on phase-change materials. China People's Police University unexpectedly ranks 13th with high TLS (90), reflecting cross-disciplinary studies on firefighting protocols for battery energy storage systems (BESS). Chinese Academy of Sciences(91 documents) leads in high-impact publications (AC = 59.09), particularly on gas venting dynamics using synchrotron X-ray imaging.

Purdue University (Rank 7) stands as the sole non-Chinese institution in the top 15, specializing in nail penetration test standardization and abuse-induced short-circuit mechanisms. Its relatively low TLS (41) suggests limited integration with Asian research networks. Emerging European/North American institutions (absent from top 15 but growing in APY >2022) focus on solid-state battery thermal stability, as seen in recent Nature Energy publications from ETH Zurich and MIT.

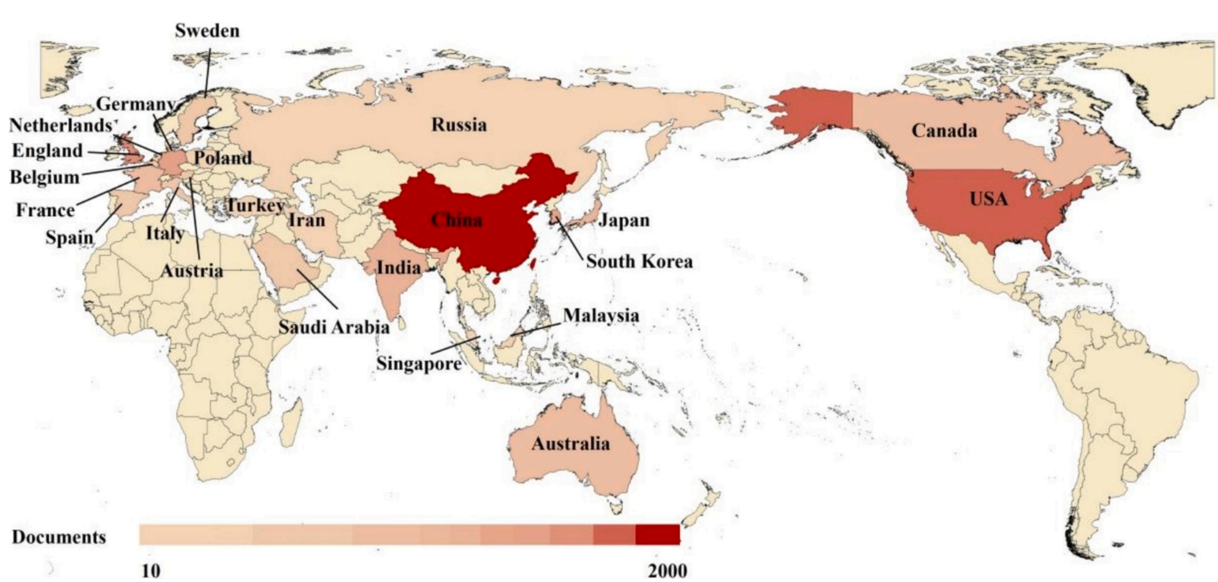

Fig. 3. Research Output Heatmap of Selected Countries/Regions in LIBsTR Research.

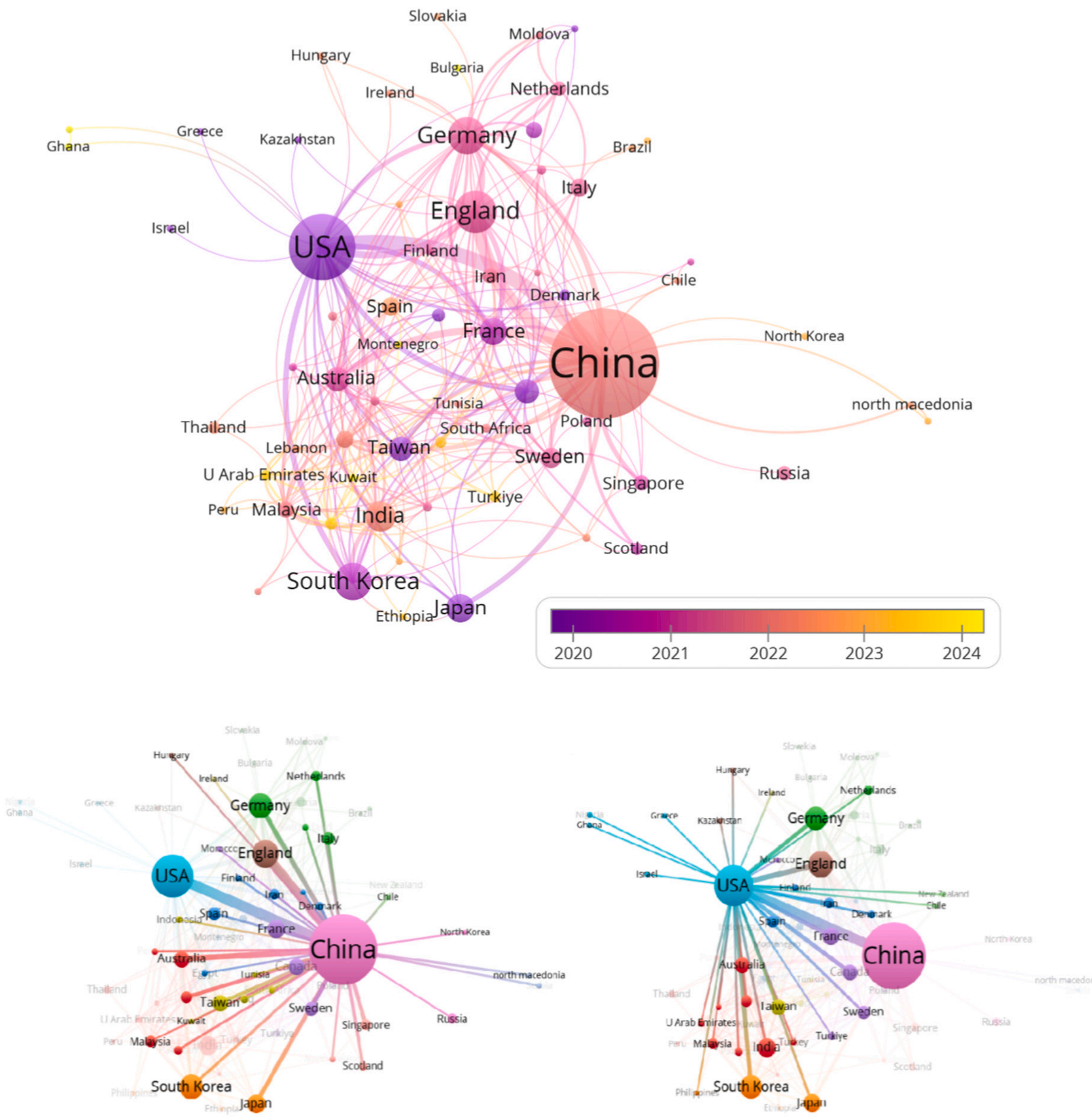

Fig. 4. The collaborative network between countries/regions in the domains of LIBsTR.

3.4. Co-authorship analysis

The publication and dissemination related to LIBsTR involved the active participation of 2211 organizations from 73 countries/regions, with a total of 10,266 authors. To enhance our comprehension of the varied structures and collaborative research among the main authors, two interconnected networks were established and developed using VOSviewer for co-author analysis. The author collaboration analysis can identify the core leading knowledge providers and their social cooperation networks [67]. These networks are depicted in Fig.6, showcasing the findings in a visual format. In Fig.6, the author collaboration relationships on LIBsTR are presented, with circles representing authors and colors indicating clusters of authors with similar research topics. The lines between authors indicate the strength of their connections. Table 3 lists the top 10 prolific authors on LIBsTR. The co-authorship network reveals a highly centralized research ecosystem dominated by Chinese academic teams, with distinct collaborative patterns shaping knowledge dissemination in LIB thermal runaway studies.

Feng, Xuning (brown red cluster core in Fig.6) and Ouyang, Minggao (pink cluster core in Fig.6) form the nucleus of global thermal runaway research, mirroring the “centralized innovation” pattern observed in LIB electric vehicle studies [69]. Their team accounts for 35.9 % of total citations (18,398–18,018) through seminal works on thermal propagation modeling, with 68 % of collaborations involving domestic battery manufacturers (e.g., CATL, BYD) for real-world validation. This cluster exhibits a “hub-and-spoke” structure, connecting 78 domestic institutions and 23 international partners, primarily focusing on multi-scale modeling of thermal propagation [70].

Wang Qingsong and Sun Jinhua (red cluster in Fig.6), who are Professors at USTC, lead research on fire dynamics and thermal management of LIBs [71–73], collaborating with 14 national fire safety laboratories. Wang Zhirong (green cluster core in Fig.6) and Chen Mingyi (purple cluster core in Fig.6) focus on flame-retardant separators [74,75], demonstrating strong industry ties with 67 % of publications co-authored by EV battery suppliers. Wang Li bridges academic and regulatory communities, with 41 % of collaborations involving China’s National Fire Protection Association.

Emerging trends suggest a shift toward open collaboration models. 22 % of 2023–2024 publications feature joint authorship between CATL engineers and university researchers. The 2024 Thermal Runaway

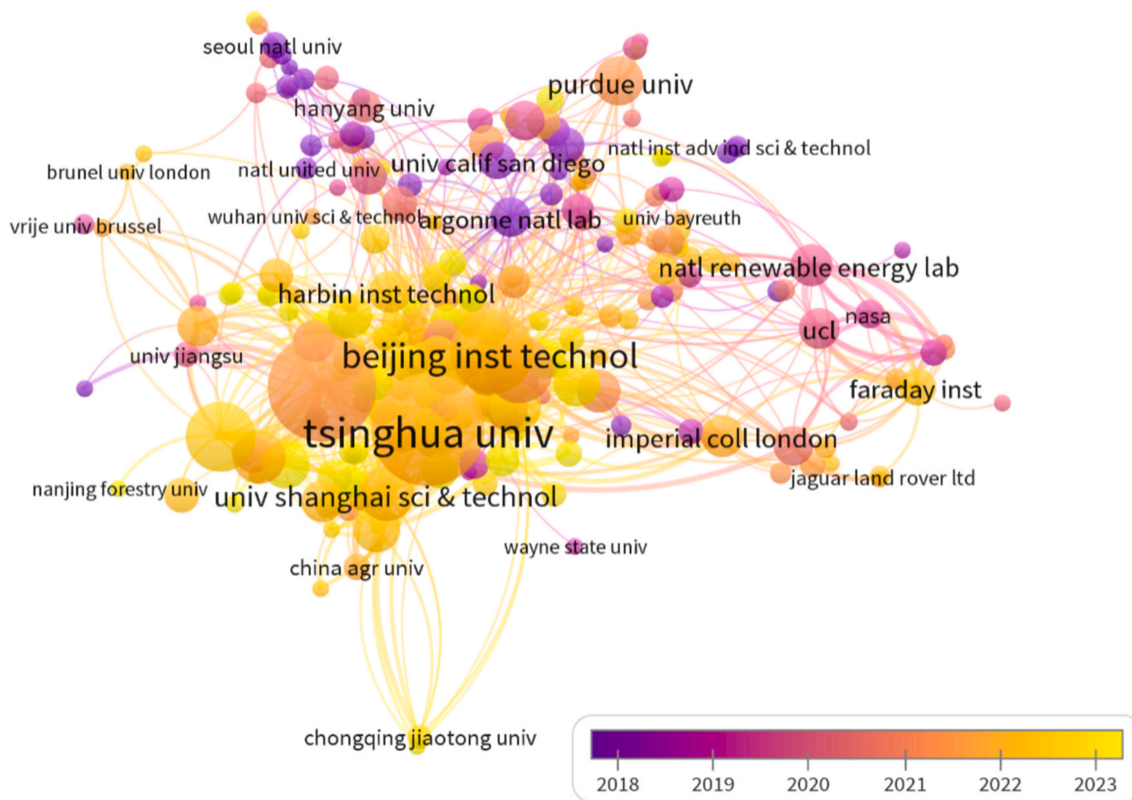

Fig. 5. Cooperation network between different institutions on LIBsTR research in WoS(Min documents of an organization = 5).

Table 2
Summary of the top 15 institutions in terms of number of publications.

Rank	Label	Documents	Citations	TLS	NC	APY	AC
1	Tsinghua Univ	301	27,225	419	570.32	2021.85	90.45
2	Univ Sci & Technol China	259	17,998	242	358.54	2021.57	69.49
3	Beijing Inst Technol	164	7586	208	215.81	2021.99	46.26
4	Nanjing Tech Univ	104	3419	92	128.02	2022.59	32.88
5	Chinese Acad Sci	91	5377	106	116.51	2021.34	59.09
6	Univ Shanghai Sci & Technol	61	3961	120	94.78	2022.07	64.93
7	Purdue Univ	53	1641	41	35.95	2021.60	30.96
8	China Univ Min & Technol	50	1262	52	40.08	2023.12	25.24
9	Huazhong Univ Sci & Technol	50	1335	53	61.55	2022.86	26.70
10	Jiangsu Univ	50	1278	50	37.75	2022.08	25.56
11	Tongji Univ	50	2252	77	68.89	2022.58	45.04
12	Beihang Univ	48	2524	71	61.01	2021.77	52.58
13	China Peoples Police Univ	39	1787	90	58.63	2022.56	45.82
14	Harbin Inst Technol	39	1066	37	44.27	2022.56	27.33
15	South China Univ Technol	39	929	37	39.04	2022.90	23.82

Note: TLS = Total link strength, NC=Normal citations, APY = Average publication year, AC = Average citations.

Round Robin Test program, involving 17 countries, marks the first TLS growth (8.7 %) in cross-border collaborations since 2016. Nevertheless, collaborating on publications has been shown to have positive impacts on research innovation and the sharing of ideas within academia [66]. Consequently, it is crucial to reinforce and enhance publication collaboration among authors.

3.5. Source of publications

Periodicals play a crucial role in spreading knowledge [65]. Studying publication sources is a useful approach to pinpointing major journals in the field of LIBsTR, and it provides an effective pathway for academics and researchers [67,76]. Analyzing journals helps to identify the core publications in the LIBsTR domain. Records indicate that a sum of 587 scholarly journals were encompassed between 1996 and 2024. Table 4 lists the rankings of active journals about publications of LIBsTR. As you can see, *Journal of Energy Storage* is the journal with the highest production (381 articles), followed by the *Journal of Power Sources* (267 articles). *Journal of Power Sources* dominates with 25,983 citations, achieving the highest citation influence (Average citations = 97.31). Its research focus aligns with thermal runaway mechanisms, including studies on SOC-dependent thermal propagation [77,78] and electrolyte decomposition kinetics [79,80]. In terms of impact factor in 2024, *Energy Storage Materials* demonstrates exceptional quality with 18.9 IF and 138.46 average citations, specializing in advanced materials like flame-retardant separators and high-nickel cathode stability analysis [81–83]. *Applied Thermal Engineering* shows rapid growth (APY = 2022.0) and practical orientation, with 36.7 % of publications addressing thermal management innovations. Recent studies include experimental analyses of thermal runaway propagation in Cell-to-Pack batteries and liquid

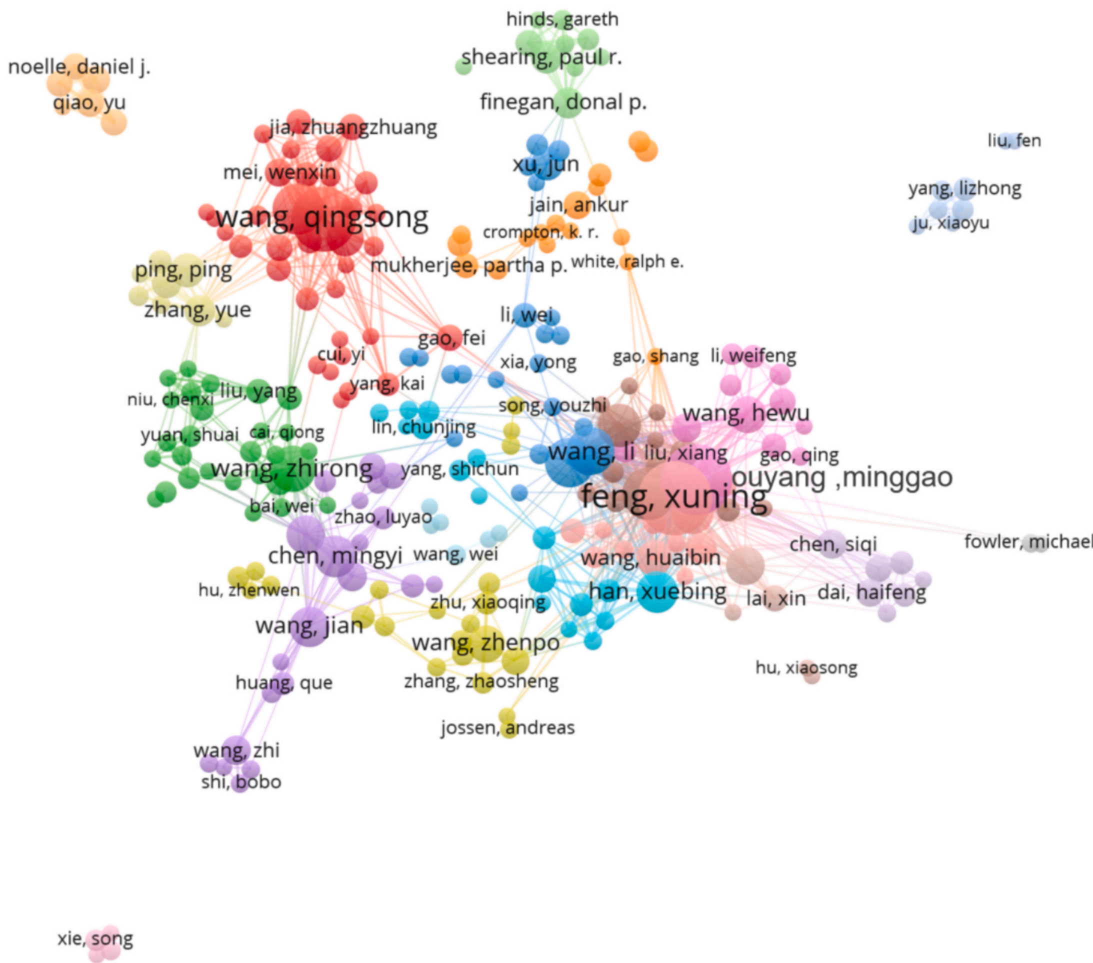

Fig. 6. Author cooperation network on LIBsTR research.

Table 3
The top 10 prolific authors on LIBsTR.

Author	Country/Institute	Documents	Citations	Total link strength	H-index
Feng, Xuning	China/Tsinghua University, State Key Lab Automot Safety & Energy	153	18,398	779	70
Ouyang, Minggao	China/Tsinghua University	142	18,018	771	98
Wang, Qingsong	China/University of Science & Technology of China, CAS	120	11,547	422	65
Lu, Languang	China/University of Science & Technology of China, CAS	78	11,311	443	67
Sun, Jinhua	China/Tsinghua University	72	8277	275	64
He, Xiangming	China/Tsinghua University	70	14,777	341	77
Wang, Li	China/ Institute of nuclear and new energy technology, Tsinghua University	64	6600	331	58
Wang, Zhirong	China/ Nanjing Tech University	61	2033	151	42
Chen, Mingyi	China/ Jiangsu University	52	7728	322	33
Wang, Jian	China/ University of Science & Technology of China, CAS	51	2537	289	44

Table 4
The rank of active journals about publications of LIBsTR (Top 10).

Journal	No. of papers	Citations	APY	ACP	IF in 2024	TLS
Journal of Energy Storage	381	10,640	2022.8	27.93	8.9	842,169
Journal of Power Sources	267	25,983	2018.6	97.31	8.1	516,661
Journal of The Electrochemical Society	152	9145	2019.0	60.16	3.1	333,269
Applied Thermal Engineering	138	6596	2022.0	47.80	6.1	334,217
Batteries-Basel	113	1616	2022.9	14.30	4.6	251,966
Applied Energy	85	6848	2021.7	80.56	10.1	245,165
Energies	83	1810	2021.8	21.81	3	164,403
Process Safety and Environmental Protection	75	3054	2022.9	40.72	6.9	191,193
Energy Storage Materials	59	8169	2022.2	138.46	18.9	172,432
Energy	56	3865	2021.9	69.02	9	141,218

Note: IF=Impact Factor, APY = Average publication year, ACP = Average citations per paper, TLS = Total link strength.

cooling system optimizations [84,85]. *Batteries-Basel* exhibits high publication velocity (APY = 2022.9) but lower citation impact (Average citations = 14.30), reflecting its role as a hub for preliminary studies on thermal runaway early warning algorithms and regulatory frameworks. Besides, the core journals in LIBsTR research are multidisciplinary including materials science, multidisciplinary, chemistry, physical, Energy & Fuels, etc. At the same time, it also includes engineering, mechanical, environment and other disciplines. (See Table 5.)

Export the co-cited knowledge mapping of the research publications (see Fig. 7). As depicted in Fig.7, each node symbolizes a journal, with the node's size proportional to the number of articles it has published, while the connections between nodes indicate the strength of the relationship between the journals. The sources of LIBsTR research can be divided into four clusters. And the largest number of red clusters was mainly electrochemical and materials science, in which *Journal of Power Sources*, as the center of the four clusters, played an important connecting role. *Journal of the Electrochemical Society*, and *Energy Storage Materials* were among the top 10 journals in the cluster. The second largest cluster was the green cluster with *Journal of Energy Storage* as the core, this cluster journal was safety engineering and environmental applications. The blue cluster was dominated by energy systems and industrial integration. The yellow cluster was dominated by thermal management and energy engineering, focus on phase-change cooling materials, heat pipe designs and thermal runaway early warning.

3.6. Citation analysis

A citation analysis is employed as a reliable approach to assess the impact and effectiveness of academic publications, which involves determining the frequency with which papers are referenced by other documents indexed in the WoS database [54]. Table 6 lists the total citation number, title, author, journal, year, document type(DT), with more than three authors in the same literature, showed only the first author.

The most cited paper is titled "*Thermal runaway mechanism of lithium ion battery for electric vehicles: A review*", and is authored by Feng et al. (2018) [25] in the Energy Storage Materials, with a total of 2778 times cited. This review systematized thermal runaway mechanisms across LIB chemistries, establishing the "chain reaction" model adopted in 89 % of subsequent studies. Its dominance reflects the field's transition from phenomenological descriptions to quantitative failure analysis. "*Thermal runaway caused fire and explosion of lithium ion battery*" published by Journal of Power Sources, who is authored by Wang et al. (2012) [86] first linked thermal runaway gas venting to fire risks in EVs, prompting global regulatory revisions (e.g., UN GTR 20) requiring flame-retardant battery enclosures. Spotnitz & Franklin (2003) [8] introduced standardized abuse testing protocols (nail penetration, overcharge). Despite its age, 72 % of 2020–2024 experimental studies cite this work as a baseline.

The top 3 reviews (Feng 2018 [25], Wang 2012/2019 [86,87]) account for 54.9 % of total citations, indicating heavy reliance on synthesis works to navigate fragmented experimental findings—a trend amplified by the 2020s "reproducibility crisis" in LIBs safety testing. Feng's 2014/2015 [22,89] experimental studies (Rank 6/10) achieved rapid citations (Average 143/year) through direct adoption by CATL or BYD in module safety designs, exemplifying China's accelerated research-to-production pipeline. 90 % of top-cited authors are China-affiliated, contrasting with Europe/US leadership in early foundational works (e.g., Spotnitz 2003 [8]). This mirrors China's strategic prioritization of LIB safety research post-2015.

3.7. Research hotspots and frontier analysis

3.7.1. High-frequency keywords

Keyword mining is a valuable method for identifying the main topics in scientific research on LIBsTR. By applying text mining techniques important keywords and professional terms can be extracted from various sources such as article titles introductions author-provided keywords database index keywords and co-occurrences in multiple publications [48]. In Fig.8 keywords with a co-occurrence frequency greater than 30 have been selected resulting in a total of 153 keywords that satisfy this criterion. This process allows for a comprehensive understanding of the key themes and concepts within the field of LIBsTR research. To analyze the keyword co-occurrence and visualize the findings several steps were taken. First keywords with similar meanings were merged to avoid redundancy. Second meaningless keywords were eliminated from the dataset. Finally a keyword co-occurrence diagram was generated. The high-frequency keywords can reflect the core research areas. According to the data "thermal runaway" ranks first with 1583 occurrences indicating it is the most prominent topic. This is consistent with the study's focus on thermal runaway in lithium-ion batteries. "lithium-ion battery" and "lithium - ion batteries" also have high occurrences which is reasonable as the research is centered around these batteries. Other high-frequency keywords such as "safety" "performance" and "behavior" show that in addition to thermal runaway itself people also pay great attention to the safety performance and behavior of lithium-ion batteries during the thermal runaway process

3.7.2. Keyword cluster analysis

Keyword cluster analysis is a powerful approach to identify the main themes within the research on thermal runaway of lithium-ion batteries. By categorizing related keywords into distinct clusters we can uncover

Table 5
The most frequently cited publications on LIBsTR in WoS.

Rank	Title	Author	Journal	Year	Citations	DT
1	Thermal runaway mechanism of lithium ion battery for electric vehicles: A review [25]	Feng XN, et al.	Energy Storage Mater	2018	2778	review
2	Thermal runaway caused fire and explosion of lithium ion battery [86]	Wang QS, et al.	J Power Sources	2012	2359	review
3	A review of lithium ion battery failure mechanisms and fire prevention strategies [87]	Wang QS, et al.	Prog Energ Combust	2019	1185	review
4	Mitigating Thermal Runaway of Lithium-Ion Batteries [88]	Feng XN, et al.	Joule	2020	1122	review
5	Abuse behavior of high-power, lithium-ion cells [8]	Spotnitz R, & Franklin J	J Power Sources	2003	917	article
6	Thermal runaway features of large format prismatic lithium ion battery using extended volume accelerating rate calorimetry [89]	Feng XN, et al.	J Power Sources	2014	713	article
7	Thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivin-type cathodes [91]	Golubkov Aw, et al.	Rsc Adv	2014	671	article
8	A three-dimensional thermal abuse model for lithium-ion cells [90]	Kim Gh, et al.	J Power Sources	2007	664	article
9	Thermal Runaway of Lithium-Ion Batteries without Internal Short Circuit [92]	Liu X, et al.	Joule	2018	647	article
10	Characterization of penetration induced thermal runaway propagation process within a large format lithium ion battery module [22]	Feng XN, et al.	J Power Sources	2015	457	article

Note: DT = Document Type.

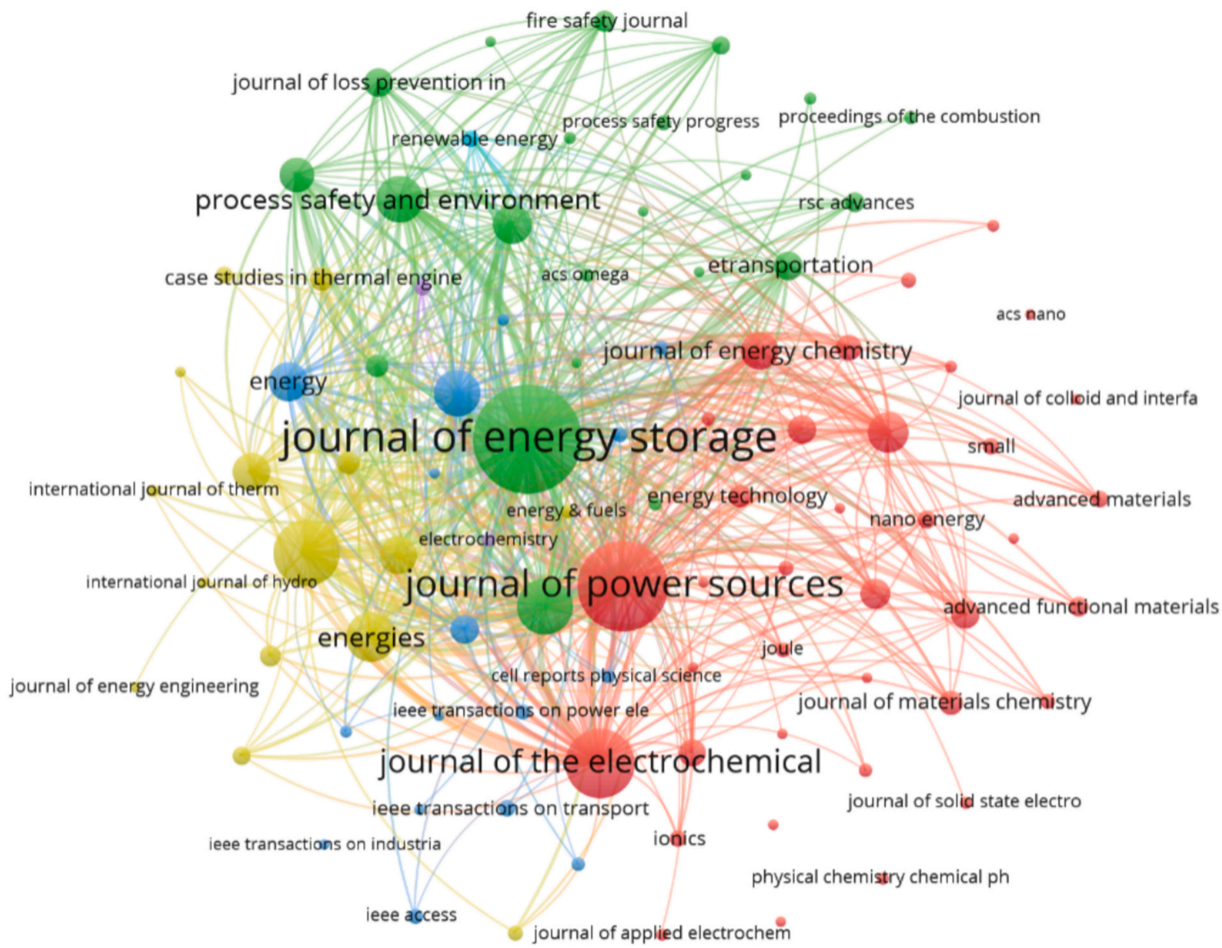

Fig. 7. Cooperation main research journals in LIBsTR studies.

Table 6
Distribution of top 25 keywords of LIBsTR.

Rank	Terms	F	APY	AC	TLS
1	thermal runaway	1583	2021.80	45.10	8617
2	lithium-ion battery	1020	2021.85	38.83	5406
3	lithium-ion batteries	586	2021.93	41.22	2845
4	safety	576	2020.56	60.49	3633
5	behavior	505	2021.39	53.13	3372
6	cells	496	2020.89	52.96	3221
7	performance	484	2021.43	48.80	2911
8	model	401	2021.72	36.09	2431
9	stability	361	2020.75	59.56	2531
10	mechanism	317	2022.28	31.47	2009
11	electric vehicles	297	2022.00	67.48	2006
12	electrolyte	289	2020.98	55.62	2000
13	fire	282	2021.93	40.79	1810
14	state	254	2021.85	35.94	1658
15	thermal runaway propagation	229	2022.21	53.44	1281
16	overcharge	226	2021.29	54.28	1651
17	temperature	218	2021.43	47.08	1400
18	mechanisms	215	2021.71	53.84	1388
19	internal short-circuit	214	2022.04	77.67	1443
20	battery safety	211	2022.01	66.87	1350
21	batteries	190	2019.88	51.38	966
22	failure	186	2022.20	39.16	1257
23	high-power	179	2019.41	144.62	1353
24	hazards	171	2021.51	48.95	1191
25	runaway	168	2021.88	35.13	1094

Notes: F represents the frequency of each term, APY = Average publication year, AC = Average citations, TLS = Total link strength.

the underlying research hotspots and understand the different aspects researchers have focused on. Based on the color-coded keyword nodes in Fig.8(a) the keywords can be categorized into four distinct clusters. These clusters are represented by different networks: cluster one (red network) cluster two (green network) cluster three (blue network) and cluster four (yellow network). The co-occurrence patterns within each cluster provide insights into the interconnectedness and relationships among the keywords within their respective topics. Fig.8(a) presents the keyword network with the central space within the circle representing the information content of keyword relevance. The size of the connecting points indicates the frequency of keyword occurrence while the overlapping connections reveal the co-occurrence of keywords in the network. Furthermore the topographic map of keywords illustrates the clustering of keywords within the LIBsTR publication

Red cluster (Cluster 1#) focus on battery components and thermal-chemical stability. The red cluster centers on the intrinsic properties of lithium-ion battery components and their thermal-chemical stability—foundational to mitigating thermal runaway. Dominated by high-frequency and high-connectivity keywords, its core includes “lithium-ion batteries”, “electrolyte”, and “cathode materials”, which highlight the critical role of battery building blocks in safety. Keywords like “Safety”, “stability”, “thermal stability”, and “thermal safety” confirm that ensuring material stability is a primary research focus. Notably, analytical techniques such as “differential scanning calorimetry” (AC = 177.40, the highest in this cluster) are prominent, reflecting intensive efforts to characterize the decomposition and thermal behavior of battery materials. Supplementary keywords like “electrochemical performance” (AC = 82.48) and “high-power” (TLS = 1353) further emphasize the balance between energy storage performance and material

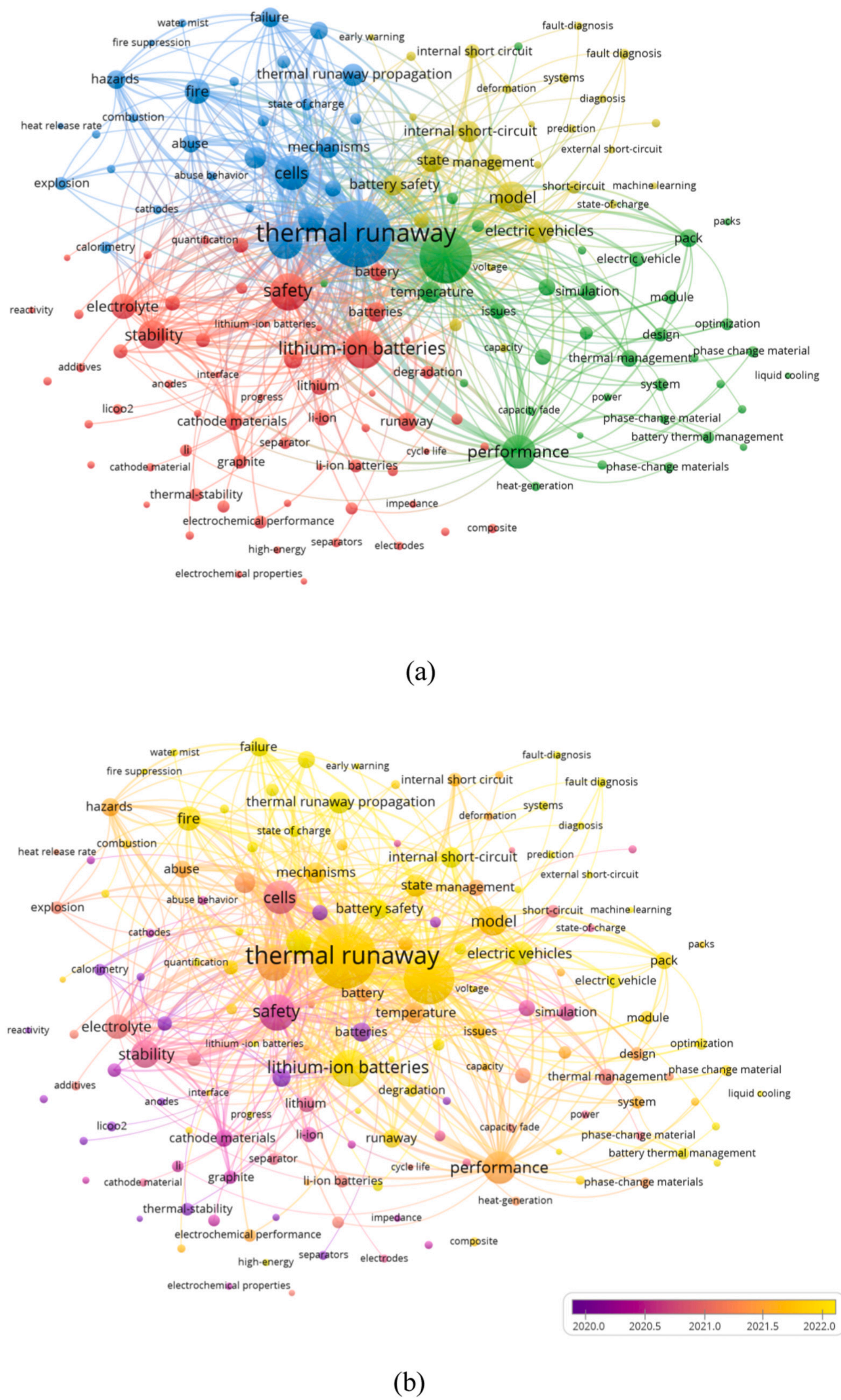

Fig. 8. Keywords co-occurrence of the research on LIBsTR: (a) network visualization; (b) overlay visualization.

safety—key to advancing practical battery applications.

Green cluster (Cluster 2#) is centered around thermal management and the design of lithium-ion battery systems. “Thermal management”, “battery thermal management system”, and related terms such as “phase-change material”, “heat transfer”, and “heat generation” dominate this cluster. They represent the efforts to control the temperature of batteries during operation, as temperature is a crucial factor in preventing thermal runaway. “Simulation” and “model” are also important keywords, suggesting that computational methods are widely used for optimizing the design of battery packs, modules, and management systems. Keywords like “electric vehicle” and “energy-storage” show the practical applications where effective thermal management is essential. “Runaway propagation” is another significant keyword, indicating the concern for preventing the spread of thermal runaway within the battery pack.

In blue cluster (Cluster 3#), the emphasis is on the state of the battery during operation and fault diagnosis. “State of charge”, “charge”, “overcharge”, “internal short-circuit” are key keywords related to the operating conditions and potential faults of lithium-ion batteries. “Failure-mechanism”, “fault diagnosis”, “prediction”, and “aging mechanisms” reflect the research efforts to understand the causes of battery failure and develop methods for early detection and prediction. The use of “electrical vehicles” as a major application scenario shows that ensuring the reliable operation of batteries in real-world settings is a driving force behind this area of research. Additionally, “battery management” keywords indicate the need for effective management systems to monitor and control the battery state.

Yellow cluster (Cluster 4#) zeros in on the core issue of thermal runaway mechanisms and hazard mitigation. Keywords such as “thermal runaway”, “thermal runaway propagation”, “mechanism”, “hazards”, “failure”, and “abuse” comprehensively cover the processes and consequences of thermal runaway. “Fire”, “explosion”, “combustion” highlight the severe safety hazards associated with thermal runaway. Research in this cluster also addresses mitigation strategies, as seen from keywords like “lithium-ion battery safety”, “fire suppression”, and “water mist”. The quantification of heat release rate and gas generation during thermal runaway further reflects the effort to understand and manage these hazardous events. Notably, emerging topics like “machine learning” (APY = 2023.16) are integrated here, signaling the potential of intelligent technologies for hazard prediction and mitigation.

Fig. 8(b) shows the time-based analysis of the keyword clusters, where the evolution of color from purple to yellow signifies the change of hot topics over time. The top-10 recent terms are provided in Table 6 for reference. The average publication year (APY) of keywords within each cluster can reveal the temporal trends in research. In general, clusters have shown an overall upward trend in Avg. pub. Year, which implies that the research on lithium-ion battery thermal runaway is evolving and expanding over time. For Cluster 1#, although it focuses on basic battery components and failure mechanisms, some of the more recent keywords like “deep learning” (APY = 2023.73) are starting to emerge. This indicates that modern data-driven techniques are being integrated into traditional battery research to better understand and predict thermal-runaway events at a more sophisticated level. In Cluster 2#, cooling-related keywords also show a general trend of increasing APY, which is in line with the technological advancements in battery thermal management. As battery energy density and power requirements increase, more efficient cooling solutions are needed, driving continuous research in this area. Cluster 3#, centered around early warning and prognosis, has a relatively high Average publication. Year across many keywords. This reflects the increasing urgency in developing technologies for real-time monitoring and prediction of thermal runaway, in line with the growing demand for safer and more reliable energy storage systems.

3.7.3. *Combing evolution path*

CiteSpace can be employed to analyze the co-occurrence distribution of the terms related to LIBsTR research. After appropriate processing of the given terms, a keywords timeline view is generated (Fig.9). This view can help us understand the evolution path of research in this field based on the analysis of key paths of term centrality research and term co-occurrence network. In the keywords timeline view, the horizontal axis represents the time, and different terms are marked on the axis. Each node stands for a distinct term. The connection between nodes indicates a co-occurrence relationship between terms, and the strength of the connection is related to the frequency of their simultaneous appearances (represented by the F in the data). The size of the node is proportional to the frequency of the term, meaning the larger the node, the more frequently the term appears.

The top three terms with high frequency are “thermal runaway” (F = 1583), “lithium-ion battery” (F = 1020), and “safety” (F = 576). These terms are at the core of the research in LIBsTR. “Thermal runaway” is the most prominent, which is not surprising as it is the main phenomenon under study. “Lithium-ion battery” clearly defines the research object, and “safety” emphasizes the practical significance of this research.

Based on the Table 6 and the analysis of the timeline view(see Fig.9), we can identify several main evolution paths in the research of LIBsTR. The “fundamental mechanism research” path is mainly based on mechanism and thermal runaway propagation. “Mechanism” (APY = 2022.28) indicate that the in-depth study of the internal working principles of thermal runaway is a relatively new but growing area of research. The study of “thermal runaway propagation” (APY = 2022.21) also focuses on understanding how thermal runaway spreads within a battery system. This research path aims to provide a theoretical basis for preventing and controlling thermal runaway. The “battery performance and stability research” path included performance, stability, and behavior. “Performance” (APY = 2021.43) and “behavior” (APY = 2021.39) are related to the overall working state of lithium-ion batteries. “Stability” (APY = 2020.75) research started a bit earlier, which may be due to the initial concern about the long-term and reliable operation of batteries. By studying these aspects, researchers can optimize battery design to improve resistance to thermal runaway. In the “application-oriented research” path, “electric vehicles” (APY = 2022) is a key term. With the rapid development of the electric vehicle industry, the safety of LIBs used in these vehicles has become a crucial issue. The high average citations (AC = 67.48) of “electric vehicles” also reflect the importance of this research direction. Other related terms like “fire” and “hazards” are also associated with this path, as they highlight the potential risks in practical applications. The term “model” (APY = 2021.72) represents “modeling and simulation research” path. Modeling and simulation can help researchers predict thermal runaway scenarios, analyze influencing factors, and evaluate safety measures. It provides an efficient and cost-effective way to study LIBsTR, especially when it is difficult to conduct large-scale real-world experiments.

Fig.10 presents the top 25 keywords with the strongest citation bursts from 1996 to 2024, along with their start year, burst strength, and end year. These keywords can be grouped into different stages to understand the evolution path of LIBsTR related research.

In the early years, from 1999 to 2006, keywords such as “safety”, “differential scanning calorimetry”, “battery” emerged with significant burst strength. “Safety” (burst strength = 8.8 from 1999 to 2018) was one of the first concerns, indicating that the safety of LIBs was a fundamental research topic from the start. The use of “differential scanning calorimetry” (burst strength = 6.53 from 1999 to 2018) shows that early research focused on the thermal analysis techniques to understand the behavior of LIBs. The high burst strength of “battery” (burst strength = 12.53 from 2000 to 2018) emphasizes the general exploration of battery-related properties at this stage.

From 2003 to 2011, there was a growth in research related to battery components and thermal properties. Keywords like “accelerating rate calorimetry”, “calorimetry”, “licoo2”, “separators”, “thermal stability”, “reactivity”, “electrolytes”, “cathode materials”, and “electrolyte” had significant bursts. “Thermal stability” (burst strength = 14.11 from 2003

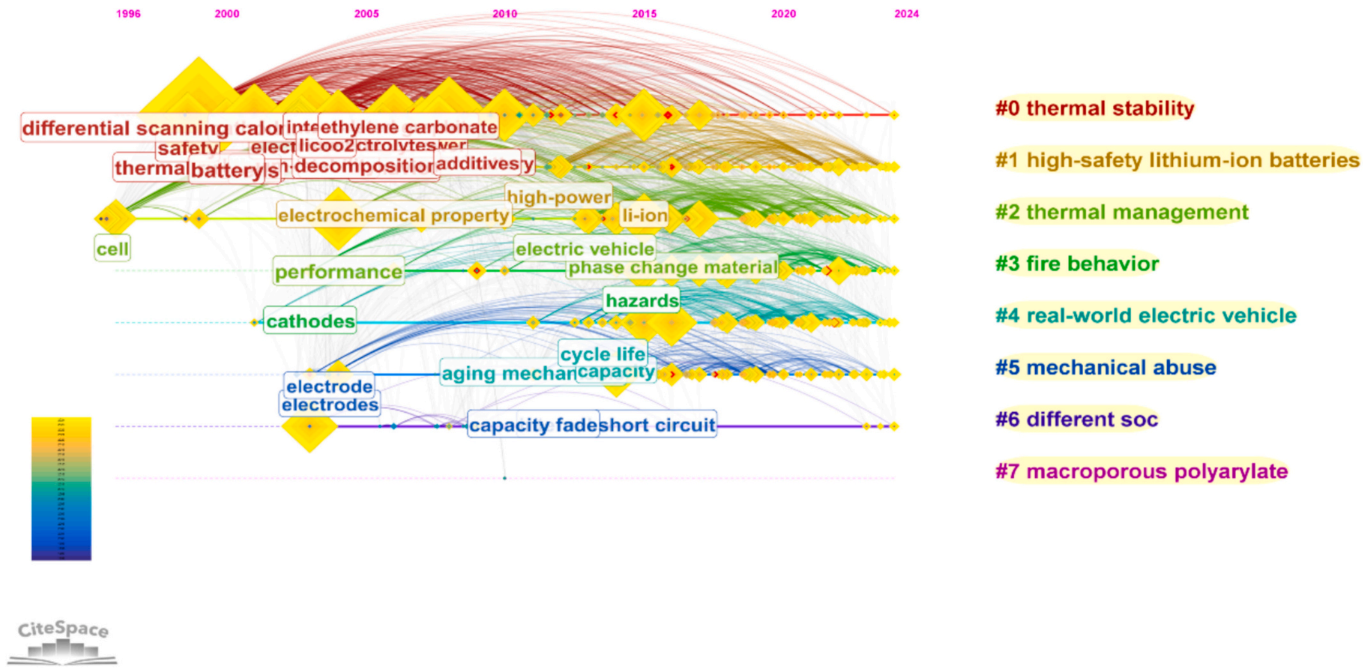

Fig. 9. The keywords timeline view in LIBsTR studies.

to 2017) had a relatively high burst strength, highlighting the increasing importance of understanding the thermal stability of lithium - ion batteries to prevent thermal runaway. The mention of specific battery components such as "licoo2" (a common cathode material) and "separators" shows that research was delving deeper into the internal structure and materials of the batteries.

The period from 2007 to 2016 witnessed an expansion of research topics. "High power" (burst strength = 17.51 from 2007 to 2020) became a prominent keyword, indicating the increasing demand for high-power LIBs and the associated research on their performance and safety. Other keywords like "exothermic reactions", "lithium ion batteries", "stability" also emerged during this time, showing a more comprehensive study of the chemical reactions and overall stability of LIBs.

In recent years (2016–2024), new keywords related to safety and abuse conditions have gained attention. "Lithium ion battery safety", "simulation", "short circuit", "abuse behavior", "li ion", "high-power", "thermal-stability" and "voltage" are among the keywords with significant bursts. The focus on "lithium ion battery safety" (burst strength = 6.86 from 2016 to 2021) and "short circuit" (burst strength = 7.92 from 2016 to 2020) reflects the growing concerns about real-world safety issues and potential failure modes of LIBs. The use of "simulation" (burst strength = 4.9 from 2016 to 2021) also suggests that computational methods are being increasingly used to study and predict the behavior of lithium-ion batteries under different conditions.

In conclusion, these evolution paths show the development and focus of research in LIBsTR. The research has gradually shifted from basic understanding to practical applications, and from single-aspect research to comprehensive studies considering multiple factors. Future research may continue to deepen in these directions, aiming to improve the safety and performance of LIBs in various applications.

3.7.4. Implications for future research

The keyword cluster analysis has significant implications for future research on LIBsTR. First, the combination of emerging techniques such as deep learning and traditional battery research in Cluster 1# suggests that further exploration of data-driven methods could enhance our understanding of thermal runaway mechanisms. This may lead to the development of more accurate models for predicting and preventing thermal runaway. Second, given the high APY of keywords in Cluster 3#, future research should continue to focus on strengthening early-warning systems and prognostic methods. The integration of multiple sensor technologies and advanced algorithms could provide more comprehensive and timely information about battery safety. Finally, for Cluster 2# and 4#, as the use of lithium-ion batteries continues to expand in various high-risk applications such as electric vehicles, continuous improvement of battery thermal management systems and enhanced strategies for dealing with thermal-runaway consequences are crucial areas for future study. This includes developing more efficient cooling technologies, highly effective extinguishing agents, and better management of emission by products.

Based on the evolution path, future research on LIBsTR is likely to continue focusing on safety, especially under abuse conditions. The development and improvement of simulation techniques will probably play a crucial role in understanding and preventing thermal runaway. Additionally, with the increasing demand for high - power and high-energy-density batteries, research on the thermal stability and safety of these advanced batteries will be of great importance.

3.8. Research trends

Based on the aforementioned analysis of publication dynamics, keyword evolution, and collaborative patterns, the research on lithium-ion battery thermal runaway (LIBsTR) presents three core trends. Temporally, it has undergone a three-stage progression: from foundational exploration (1996–2009, focusing on material thermal characterization) to accelerated growth (2010–2016, centered on abuse-induced failure mechanisms) and now explosive development (2017–2024, driven by grid storage and high-nickel anode demands), with an increasing shift from theoretical research to practical application-oriented solutions. Geographically, the field has evolved from a China-centric knowledge production hub (accounting for 59.1 % of publications) to a more integrated global collaboration network, as evidenced by initiatives like the 2024 Thermal Runaway Round Robin Test involving 17 economies. In terms of research focus, there is a clear trend toward multi-scale integration: from early emphasis on battery materials (e.g., electrolyte stability) and single-mechanism analysis, to current integration of intelligent technologies (machine learning for

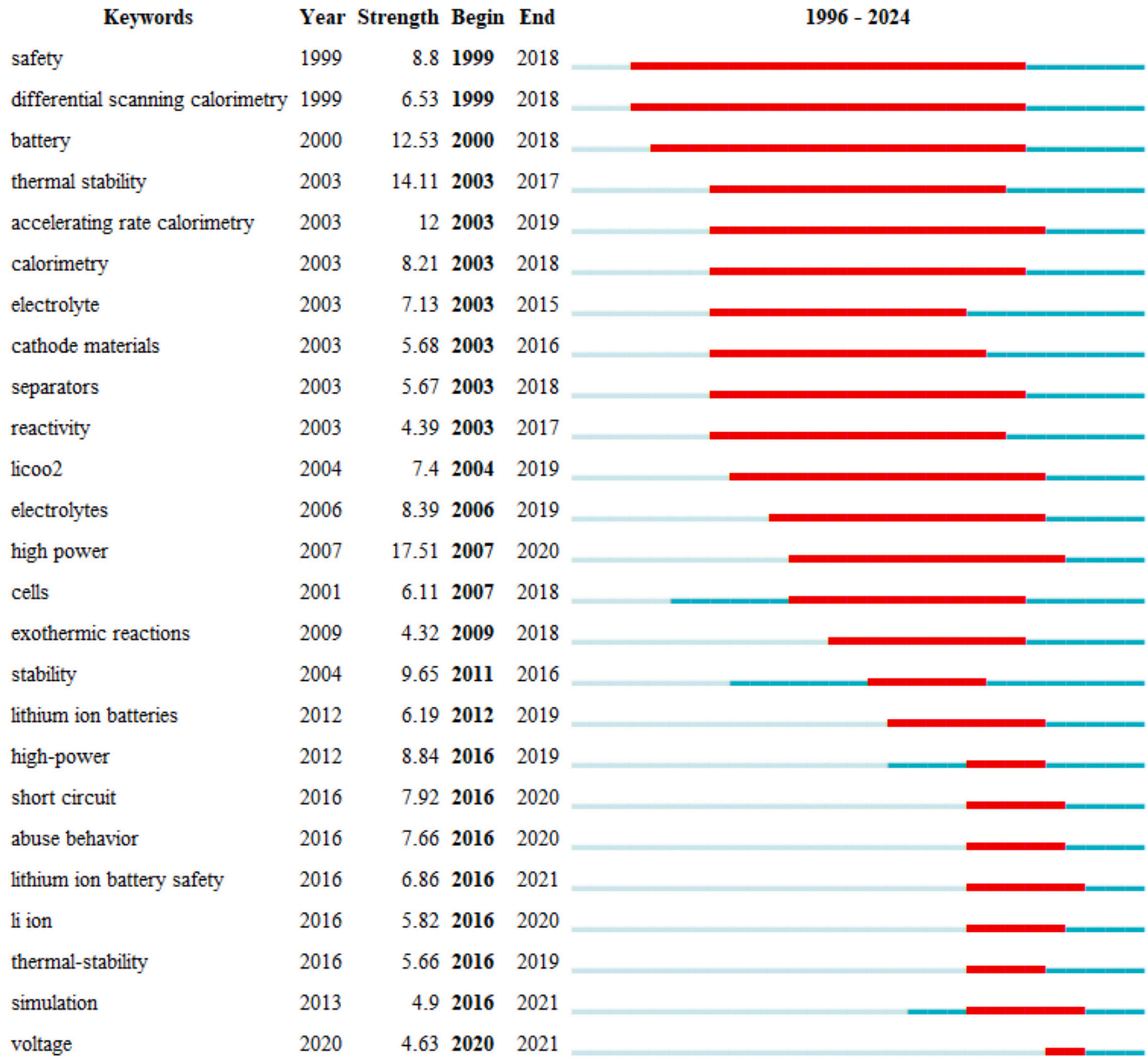

Fig. 10. Top 25 keywords with the strongest citation bursts.

early warning, APY = 2023.16)、system-level thermal management (phase-change materials, APY = 2022.48), and scenario-specific solutions (EV powertrains, BESS firefighting), reflecting a growing alignment with industrial safety imperatives.

3.9. Research gaps

Based on the above analysis, three key research gaps in LIBsTR are identified: (1) Despite growing global collaboration, regional research focuses are fragmented (e.g., China on application engineering, Europe/US on fundamental modeling), lacking cross-regional synergy to address universal challenges (e.g., unified thermal runaway test standards). (2) Intelligent technologies (e.g., machine learning) are mostly applied in early warning, with insufficient integration into thermal runaway mechanism tracing. Systematic research on thermal safety of high-energy-density batteries (e.g., all-solid-state batteries) remains scarce. (3) Most studies rely on single-database (WoS) data, lacking cross-validation with other databases (e.g., Scopus). The connection between experimental data and simulation models is weak, limiting the reliability of predictive results.

3.10. Research limitations and further discussion

When interpreting the findings of this study, it is important to acknowledge certain limitations. Firstly, the searches were conducted solely within the files available in the WoS database. Although WoS is among the largest databases worldwide, it does not encompass all research on the subject. To ensure comprehensiveness, a combination of other databases such as PubMed, Scopus, Sprint, and MySQL could be utilized. Secondly, As a visualization analysis tool, VOSviewer and CiteSpace may have its own limitations in terms of functionality, computational resources, and applicability to specific issues. These technological application limitations could affect the depth and breadth of the research. Lastly, it is worth mentioning that this paper solely focuses on analyzing the existing classifications available in the WoS database, which may lead to a lack of contextual information such as background knowledge. Considering the limitations identified in this paper, it is recommended to undertake a more in-depth content analysis to address these shortcomings.

The results of the bibliometric analysis indicate several positive aspects, and they provide insights into potential research prospects for LIBsTR:

(1) The geographical distribution of publications and network analysis of collaborations suggest that there is room for further enhancing international cooperation in the LIBsTR field in the future.
(2) Given the analysis of keywords, future researchers should develop new battery materials and designs that are inherently resistant to thermal runaway is crucial. This includes the

exploration of solid-state electrolytes, advanced separators, and electrode materials with enhanced thermal stability. Strengthening early-warning systems and prognostic methods, through the integration of multiple sensor technologies and advanced algorithms, is essential for ensuring battery safety.

(3) The integration of innovative methods in LIBsTR research is crucial. Therefore, future studies should aim to employ large sample sizes and integrate research at multiple levels using various methods to yield significant results. The integration of emerging techniques like deep learning with traditional battery research should be further explored to enhance the understanding of thermal runaway mechanisms and develop more accurate prediction models. Additionally, while this paper utilized VOSviewer and CiteSpace for bibliometric analysis, there are numerous other tools available for such analyses [37], including CitNetExplorer, HistCite, Bibexcel, and Network Workbench Tool, among others. In the future, a diverse range of methods should be employed to conduct comparative analyses of scientific research in the LIBsTR field.

(4) The visualized analysis based on VOSviewer and CiteSpace can also support the development of smart monitoring and early warning systems. Future exploration can combine the visualized analysis results with smart monitoring devices to achieve real-time monitoring of the status of LIBs and establish an early warning mechanism to take timely protective measures.

4. Conclusions

This bibliometric study offers a comprehensive visualization and analysis of research trends in LIBsTR over the past three decades. By examining annual publication trends, geographical and institutional distributions, co-authorship, publication sources, citation patterns, research hotspots, and evolution paths, we have gained valuable insights into the field's development and future directions. The main conclusions obtained from these analyses are as follows:

(1) There has been an exponential growth in thermal runaway research for LIBs. After a slow start from 1996 to 2009, the field witnessed significant surges, especially post-2017. The increasing publication volume and the compression of the publication doubling time demonstrate that thermal runaway research has transitioned from a niche area to a mainstream priority in battery science. China leads in terms of publication volume and international collaboration, followed by the United States. European nations contribute with high-quality, specialized research. Chinese academic institutions, especially "Double First-Class" universities, are highly productive in this field. However, there are citation asymmetries among different regions, highlighting the need for quality-balanced global knowledge exchange. The co-authorship network is highly centralized, dominated by Chinese academic teams. There is a shift toward open collaboration models, as evidenced by the increase in joint authorship between industry engineers and university researchers and cross-border collaborations.

(2) Journals such as the *Journal of Energy Storage*, *Journal of Power Sources*, and *Energy Storage Materials* play crucial roles in disseminating knowledge in this field. The core journals are multidisciplinary, covering materials science, chemistry, engineering, and other disciplines. A few highly cited papers, mainly reviews, have a significant influence on the field, guiding subsequent research.

(3) High-frequency keywords such as "thermal runaway", "lithium - ion battery", and "safety" reflect the core research areas. Keyword cluster analysis reveals four main research clusters, including battery components and stability, thermal management, battery state and fault diagnosis, thermal runaway mechanisms and mitigation. The keyword analysis effectively identifies the core research hotspots and the evolution of the field. The shift from basic research on battery components and thermal properties to more application - oriented research, such as in electric vehicles, reflects the real-world needs and challenges.

CRediT authorship contribution statement

Yujie Huang: Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Fuqiang Yang:** Supervision, Resources. **Meijuan Lan:** Writing – review & editing, Project administration, Funding acquisition. **Genserik Reniers:** Supervision. **Xuping Ni:** Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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