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Global Trend for Waste Lithium-Ion Battery Recycling from 1984 to 2021: A Bibliometric Analysis

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Abstract: With the massive use of lithium-ion batteries in electric vehicles and energy storage, the environmental and resource problems faced by used lithium-ion batteries are becoming more and more prominent. In order to better resource utilization and environmental protection, this paper employs bibliometric and data analysis methods to explore publications related to waste lithium-ion battery recycling from 1984 to 2021. The Web of Science core set from the SCIE online database was used for this article. These findings demonstrate a considerable increase trend in the number of publications published in the subject of recycling used lithium-ion batteries, with a natural-sciences-centric focus. Argonne National Lab, Chinese Academy of Sciences, and China Academic and Scientific Research Center are the top three institutions in terms of quantity of papers published. The affiliated journals corresponding to these three institutions also have high impact factors, which are 106.47, 44.85, and 58.69, respectively. In comparison to comparable institutes in other nations, the American Argonne National Laboratory supports 223 research articles in this area. China and the US make up the majority of the research's funding. The two key aspects of current lithium-ion battery recycling research are material structure research and environmentally friendly recycling. Nevertheless, high-capacity lithium-ion batteries, waste lithium-ion integrated structures, and gentle recycling of spent lithium-ion batteries will be the major aspects of study in the future. It is hoped that the above analysis can bring new ideas and methods to the field of waste lithium-ion battery recycling and provide a basis for the subsequent research and application of waste lithium-ion battery recycling.

Keywords: spent lithium-ion battery recycling; bibliometric; data analysis; VOS Viewer; CiteSpace

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1. Introduction

With the fast advancement of industry and the improvement of individuals' expectations for everyday comfort, different electronic gadgets have entered in all parts of individuals' lives, and, hence, the creation and utilization of an enormous number of battery-powered batteries [1]. Among battery-powered batteries, lithium-ion batteries are generally utilized in wind and sun-oriented power plants, hydroelectric and nuclear power stockpiling frameworks [2,3], as well as in phones, PCs, electric vehicles, military gear, and other different fields as a result of their light weight, long cycle life, high unambiguous energy, wide working temperature, and natural security [4]. According to an investigation report, the worldwide market for lithium-ion batteries will be valued at USD 139 billion by 2026 [5]. Moreover, the help life of lithium-ion batteries is by and large 3 to 5 years. Consequently, the quantity of consumed lithium-ion batteries will increment before long [6]. By 2030, the quantity of lithium-ion battery packs consumed internationally will surpass 11 million tons [7]. At this point, there will be an enormous number of end-of-life lithium-ion batteries. On the off chance that they are not dealt with as expected, it will represent a danger to the climate and human wellbeing. Curiously, barely any endeavors have been made to gather orderly information on the scale and extent of this hazardous logical examination, regardless of the foundation of quickly expanding end-of-life volumes. The worldwide scene of utilized lithium-particle battery research has never been unequivocally portrayed in a quantitative way in the writing previously. Meanwhile, squander lithium particle likewise has a high monetary worth, due to the enormous measure of weighty metals, natural synthetic substances, and plastics in the accompanying extents: 5%–20% Co, 5%–10% Ni, 5%–7% Li, roughly 15% natural synthetic substances, and 7% plastics, which are higher than those tracked down in normal minerals [8–12]. What is more, spent lithium-ion batteries additionally contain poisonous and combustible natural electrolyte ($LiBF_4$ and $LiPF_6$ disintegrated in natural dissolvable), which is thoroughly examined as both an alluring auxiliary asset and ecological contamination [13,14]. Currently, three typical methods for the recycling of spent LIBs are biometallurgical [15], pyrometallurgical [16], and hydrometallurgical routes [17]. Interestingly, in spite of this foundation, hardly any endeavors have been made to gather methodical information on the scale and extent of this hazardous logical examination. The worldwide display of utilized lithium-particle battery research has never been unequivocally depicted in a quantitative way in previous papers.

As a tool to deal with the vast amount of literature, the bibliometric method has already been widely applied as an analysis technique for scientific production and research status in many disciplines of science and engineering [18,19]. Hence, this paper dissects the reusing of utilized lithium-ion batteries remembered for science citation index (SCI) for the period 1989–2021. It expects to comprehend the exploration advancement patterns in this field in the past 30 years and gives helpful reference data to proficient specialists in this field.

2. Methods

2.1. Data Sources

Data were retrieved from the Web of Science (WoS) Science Citation Index Expanded (SCI-EXPANDED) web database. WoS contains the world's most important and influential research papers and is recognized as the world's most important literature search platform, considering the comprehensiveness, timeliness, and frontiers of the paper sources; the keywords of this study are TS = ("spent lithium-ion batter*" OR "spent Li-ion batter*" OR "waste lithium ion batter*" OR "waste Li-ion batter*" OR "$LiCoO_2$"OR"$LiFePO_4$" OR "$LiMn_2O_4$" OR "lithium cobalt oxides" OR "lithium iron phosphate" OR "lithium manganese oxide" OR "ternary batter*" OR "ternary material*" AND "recover*" OR "reuse*" OR "resource utilization"). The pursuit language was set to "English", writing scan type for papers and articles, and the inquiry covered the period 1984–2021 and yielded a sum of 5487 pertinent papers.

2.2. Research Methods

Relevant features of the articles were analyzed using bibliometric methods. Bibliometrics is the cross-cutting science of quantitative analysis of all knowledge carriers using mathematical and statistical methods. It is a combination of mathematics, statistics, and documentation, a comprehensive body of knowledge with a focus on quantification. Scientific statistical analysis of relevant papers is proceeded using CiteSpace and VOS Viewer software [20,21]. CiteSpace is an information visualization software developed by Prof. Chen C. M [22,23], focusing on the analysis of potential knowledge contained in scientific papers. It is a multifaceted, time-phased, dynamic citation visualization and analysis software gradually developed in the context of scientometrics, data, and information visualization. It can provide knowledge clustering and distribution in citation space and, also, provide a co-occurrence analysis of knowledge units, such as authors, institutions, countries/regions, etc. VOS Viewer is a bibliometric software developed by Leiden University that effectively presents the structure, evolution, and relationships of collaborations in a field of knowledge and assesses the current state of research and hot spots in a field through visualization [24,25]. Considering the merits of the 2 software packages, in this study, a combination of CiteSpace and VOS Viewer software was used to conduct a metrological analysis of papers in the field of used lithium-ion battery recycling [26–30].

3. Results and Analysis

3.1. Literature Type and Publishing Trend Analysis

3.1.1. Literature Type Analysis

In the Web of Science search system, a total of 5487 records were obtained that met the requirements. Research articles (5300 or 95%) were the most common type, followed by reviewer article (153 or 4%) and others (34 or 1%, including editorial material, meeting abstracts, news stories, letters, revised articles). Because research papers can more reliably reflect research trends [31], just information connected with research papers is viewed in this paper, and the comparing bibliometric examination is performed.

3.1.2. Analysis of the Number of Papers Issued and Trends

Figure 1 shows the trend of annual issuance of waste lithium-ion batteries. It can be seen from the figure that scientists from different nations keep up with high excitement for the exploration on squander lithium-particle battery reuse, though it has been a long time since the commercialization of waste lithium-ion batteries and the quantity of papers distributed yearly has been showing a pattern of fast development. The number of papers on lithium-ion battery cathode materials included in Science Citation Index Expanded (SCI-EXPANDED) jumped from 1 in 1984 to 5487 in 2021. In general, the number of articles on squandering lithium-particle battery reuse has been expanding step by step, which demonstrates that squander lithium-particle battery reuse is continually receiving consideration and significance from researchers. Its exploration act has gone through around three phases: (1) from 1984 to 1990, it was the growing time of waste lithium-particle battery reuse. At this stage, the quantity of waste lithium-ion batteries was restricted, and the connected fields of waste lithium-particle battery reuse had quite recently started to show up. There are not many examinations and there are openings in certain years. The scholastic local area tries to ignore the reusing of waste lithium-ion batteries; (2) from 1990 to 2010, it was the improvement timeframe in the field of waste lithium-particle battery reuse. At this stage, the quantity of examination papers connected with squander lithium-particle battery reuse had consistently expanded and this field had, bit by bit, pulled in the consideration of researchers; (3) from 2010 to 2021, this was a dangerous period for the reusing of utilized lithium-ion batteries. This stage shows a touchy flood in the reusing of utilized lithium-ion batteries and, according to an overall point of view, vehicle possession keeps a quick vertical pattern. The blast in the market has brought extraordinary open doors, yet, additionally, likely issues. From one perspective, the substance of valuable metal assets in resigned lithium-ion batteries is a lot higher than that of regular minerals, and understanding the reusing of metal components in them is a significant method for lightening what is going on with asset exhaustion and fostering the roundabout economy of lithium-ion batteries. Then again, the reusing of involved lithium-ion batteries in huge heaps can likewise make potential contamination of the biological system. The reusing of waste batteries can altogether diminish the adverse consequence on the climate. Hence, amplifying the monetary worth of utilized lithium-particle battery reuse and decreasing its adverse consequence can ensure the steady and sound advancement of the lithium-particle battery industry.

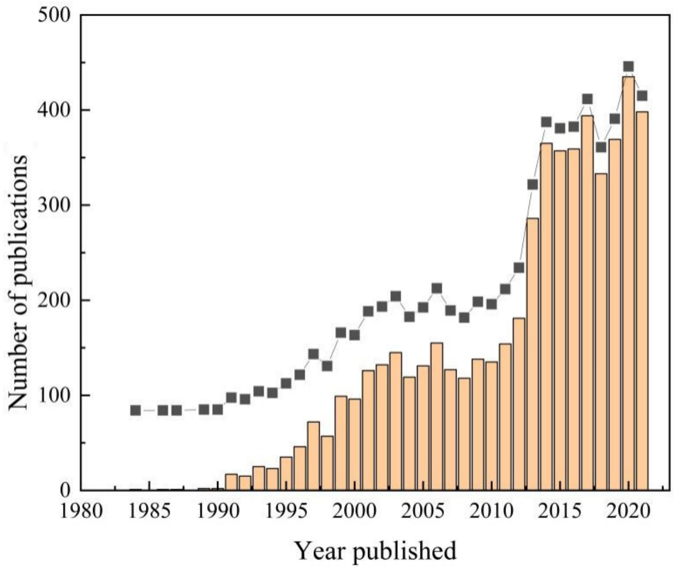

Figure 1. The number of waste lithium-ion battery recycling articles and the cumulative percentage of articles issued.

3.2. Country Analysis

3.2.1. Country Contribution Analysis

The quantity of distributions and references per article in the field of waste lithium-particle battery reuse in the previous years were dissected, and the 10 nations with the largest number of exploration papers in the field of waste lithium-particle battery reuse and their typical references per article from 1984 to 2021 were determined (Table 1). As found in Table 1, in the field of utilized lithium-particle battery reuse, the nations with more than 600 distributions are China, the United States, and Japan, with 37.78%, 19.66%, and 11.96% of the absolute number of articles given, respectively. Among the 10 nations with in excess of 110 distributions, China and India are among the emerging nations, which shows that created nations are more grounded than nonindustrial nations in this field. Among the 10 nations/districts with in excess of 110 articles, Europe represents 5, Asia for 4, and Australia is the main country from Oceania.

Table 1. Top 10 contributing countries.

Rank	Country	Documents	Citations	Average Citation/Publication	Number of Issued Articles (%)
1	China	2073	73,511	35.46	37.78
2	USA	1079	89,758	83.19	19.66
3	Japan	656	28,401	43.29	11.96
4	South Korea	593	25,603	43.18	10.7
5	Germany	310	12,369	39.9	5.59
6	France	264	15,721	59.55	4.76
7	India	203	6612	32.57	3.66
8	England	127	6070	47.8	2.29
9	Australia	123	5173	42.06	2.22
10	Spain	114	4012	35.19	2.06

In the meantime, the United States and Japan are driving in both the quantity of articles and references per paper, demonstrating that these nations have a high impact and worldwide voice in the field of waste lithium-particle battery reuse. While five of the seven early papers in the field of utilized lithium-particle battery reuse came from Japan, one and two came from the UK and Korea, respectively, and 36% of the papers before 2010 came from the US and Japan. The previous beginning laid out the predominance of the

US and Japan in this field. Conversely, albeit the result of Chinese papers is in the best three, the normal references per paper are lower. From one viewpoint, it shows that the quantity of papers distributed in China in the field of waste lithium-particle battery reuse has consistently expanded as of late.

3.2.2. Analysis of Country Clustering and International Co-Operation Patterns

First of all, using VOS Viewer to dissect the reusing aftereffects of utilized lithium-ion batteries from 32 nations, the global collaboration relationship is displayed in Figure 2a. The bigger the hub in the figure, the more archives the nation distributes. The thickness of the association corresponds to the closeness of collaboration. The thicker the association, the nearer the collaboration between nations [32]. In the past 35 years, China, Japan, the United States, France, South Korea, and Germany were the hot exploration nations of waste lithium-particle battery reuse; China in the top nations, as the most conspicuous nations, should be proof of the fast advancement of China's logical examination strength as of late. By and by, the aftereffects of the group examination were determined through the posting. These groups are sorted by the worldwide participation qualities of the sending nations, showing specific examples of global collaboration. Every hub in the figure addresses a nation, and the size of the fact of the matter is connected with the volume of articles given by that country. The lines between the focuses demonstrate the collaboration among nations, and the thickness of the lines mirrors the quantity of helpful postings. Germany, Japan, Korea, and different nations comprise cluster 1; China, the United States, Singapore, Canada, and different nations comprise group 2; France, Switzerland, Italy, and different nations comprise cluster 3. The exceptional centrality execution and high connection strength of China, the United States, South Korea, and Japan show the high global status and solid worldwide participation of the above nations in the field of utilized lithium-particle battery reuse. Among them, China has the most grounded centrality.

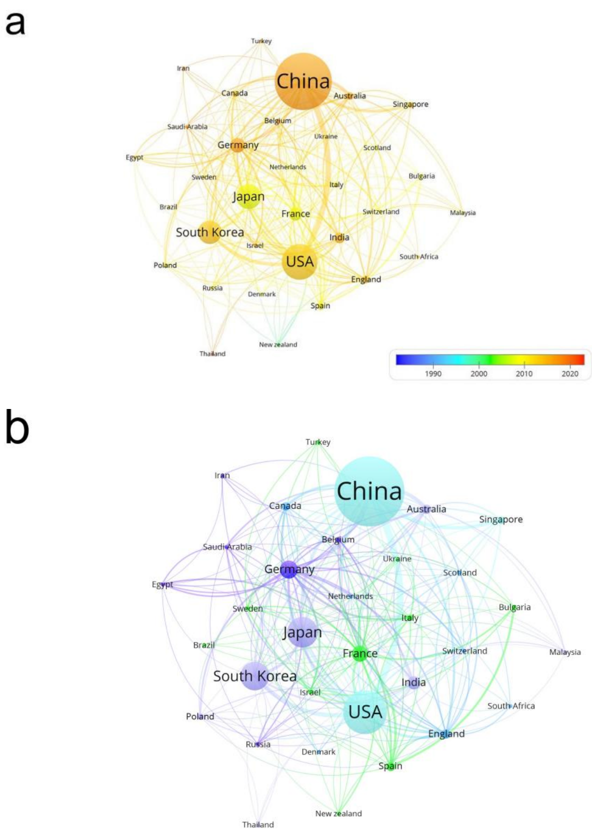

Figure 2. Country clustering and analysis of international co-operation patterns: (**a**) country co-operation relationships and (**b**) country clustering analysis.

3.3. Analysis of Issuing Institutions

3.3.1. Number of Issuing Institutions

By analyzing the institutions of the authors, it is helpful to understand the core institutions in the field of waste lithium-ion battery recycling [33,34]. A comprehensive analysis of the 10 institutions with the highest number of research publications in the field of carbon neutrality from 1984 to 2021 showed their average citation frequency per paper and number of publications were greater than 70 (Table 2).

Table 2. Top 10 journals for recycling used lithium-ion batteries.

Rank	Orginization	Country	Documents	Citations	Average Citation/Publication
1	Argonne Natl Lab	USA	223	23,742	106.47
2	Chinese Acad Sci	China	216	9688	44.85
3	Cent Acad Sci	China	110	6258	56.89
4	Natl Inst Adv Ind Sci & Technol	Japan	105	4860	46.29
5	Univ Sci & Technol China	China	91	3483	38.27
6	Tokyo Inst Technol	Japan	87	3449	39.64
7	Tsinghua Univ.	China	83	2173	26.18
8	Hanyang Univ.	South Korea	79	4788	60.61
9	Univ. Calif. Berkeley	USA	73	6571	90.01
10	Xiamen Univ.	China	71	5431	76.49

As should be visible from Table 2, 5 of the 10 organizations with the most distributions are situated in developed countries, and just the Chinese Academy of Sciences, Tsinghua University, and the University of Chinese Academy of Sciences are from a developing country. The complete reference recurrence of Argonne National Laboratory is a lot higher than different foundations, further exhibiting major areas of strength for the United States in the field of utilized lithium-particle battery reuse. As of late, a few examination organizations in China have distributed more articles in the field of waste lithium-particle battery reuse and sped up improvement; yet, a similar issue of low normal reference recurrence per article exists, and the improvement quality has more space for development.

3.3.2. Contact the Issuing Institution

From the bunching connections of the responsible foundations in Figure 3a, two fundamental helpful relationship families are framed, one fixated on China and the other on the United States, Japan, and Korea. It very well may be seen from the figure that Chinese logical examination establishments and foundations are generally firmly associated, and there is a feeble relationship with the United States, South Korea, and Japan, which might be one reason for the restricted degree of references in my country. In Figure 4b, we can see that our nation began late compared with different nations, which might be one more justification for the low reference recurrence. Over the long haul, in the advancement of waste lithium-particle battery reuse, China ought to fortify the nearby binds with different nations and continuously increment its impact in the exploration of waste lithium-particle battery reuse.

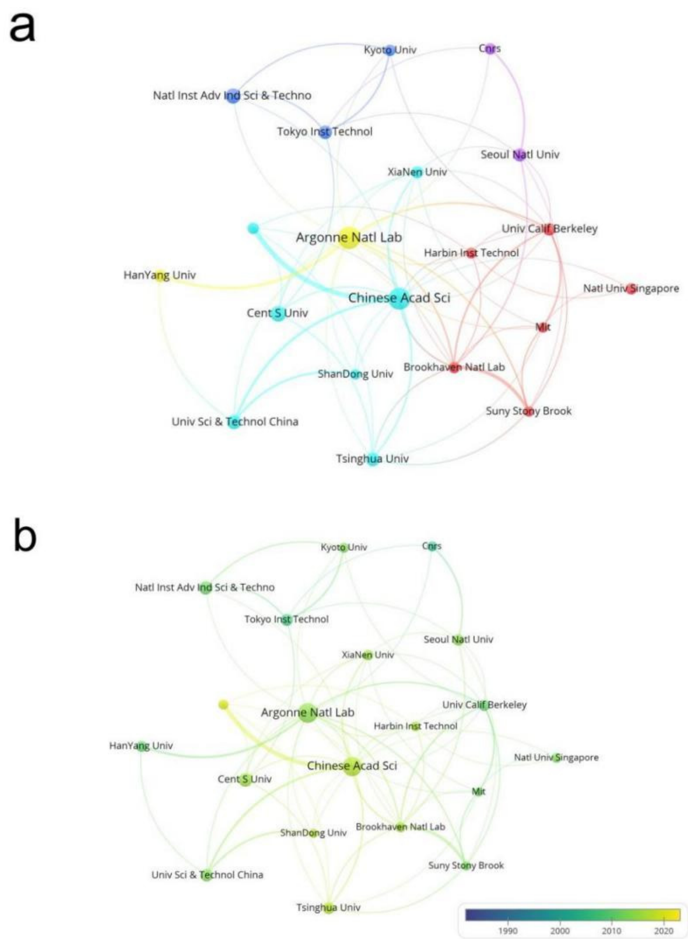

Figure 3. Contact between waste lithium-ion battery recycling issuing institutions: (**a**) institution clustering analysis (different colors, such as purple, light blue, and red, represent the different clusters they belong to, and different clusters are represented by different colors); and (**b**) institutions' co-operation relationships.

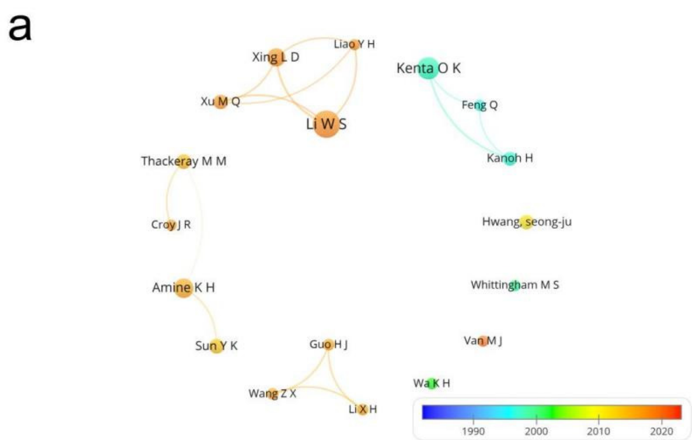

Figure 4. *Cont.*

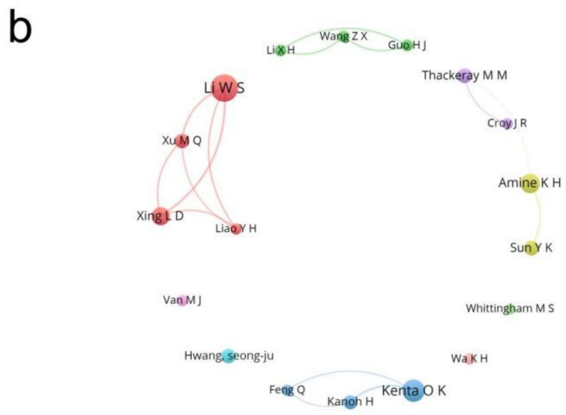

Figure 4. Spent lithium-ion battery recycling issued between the author contacts: (**a**) author co-operation relationships and (**b**) author clustering analysis.

3.4. Author Analysis of the Article

3.4.1. Number of Authors

The more dynamic examination of researchers and disciplinary groups in the field of waste lithium-particle battery reuse can be obtained from the exploration region of the paper writers. The main 10 writers in the quantity of articles distributed in the field of utilized lithium-particle battery reuse over the most recent 35 years are displayed in Table 3. As displayed in Table 3, Wei-Shan Li [35,36] of South China Normal University is the creator with the most distributions in the field of waste lithium-particle battery reuse in the past 35 years, with 55 distributions. The units to which the high-yielding creators have a place are packed in South China Normal University, Argonne National Laboratory, Hanyang University, and so forth. In addition, these foundations are in the main five of the public distribution measurements table in Table 1, showing the congruity of exploration on reusing involved lithium-ion batteries as of late in the above nations.

Table 3. Top 10 authors of articles on waste lithium-ion battery recycling.

Rank	Author	Affiliations	Country	Documents	Keywords	Average Citation/Publication
1	W S Li	South China Normal Uniersity	China	45	Electrochemical materials	34.47
2	Kenta O Oi	National Institute of Advanced Industrial Science and Technology	Japan	86	Reuse of waste materials	67.69
3	Thackeray M M	Argonne National Laboratory	USA	57	Disordered lithium spinel electrode	210.69
4	K H Amine	Argonne National Laboratory	USA	518	Battery storage materials	128.33
5	L D Xing	South China Normal Uniersity	China	134	New battery materials	39.73
6	Y K Sun	Hanyang University	South Korea	501	Energy storage	164.1
7	M Q Xu	South China Normal Uniersity	China	93	Anode and cathode materials for batteries	43.31
8	Y H Chu	Tsinghua University	China	28	Lithium polymer battery	84.32
9	H J Guo	Northeastern University	China	24	Interfacial properties	49.58
10	X H Li	Xinjiang Normal University	China	3	Basic study	49.58

3.4.2. Author or Contact

It very well may be seen from Figure 4 of the creator's affiliations that, in China, the improvement of waste lithium-particle battery reuse is fundamentally framed by the exploration group of Li Weishan of South China Normal University on electrochemical energy stockpiling innovation. In far off nations, scientific examinations on cash energy capacity materials and implanted battery structures are shaped by Michael M. Thackeray et al. of Argonne National Laboratory, USA, and Sun Y K of Korea. In this cycle, we found that Korea and Japan have shaped better ties, while, in China, we have ties fixated on our exploration group, with an absence of association with cutting-edge nations abroad. From a drawn-out viewpoint, expanding its impact in this field requires expanding close binds with nations such as the United States and South Korea.

From Figure 5b, we can see that, before 2010, US researchers had explored the field of utilized lithium-particle battery reuse, while China and Korea began to, bit by bit, explore in this field later in 2010. Contrasting the U.S., China began late. Later on, we ought to build the expansiveness of exploration around this, increment close binds with different nations, and better mirror China's global relations and collaboration in the field of waste lithium-particle battery recycling.

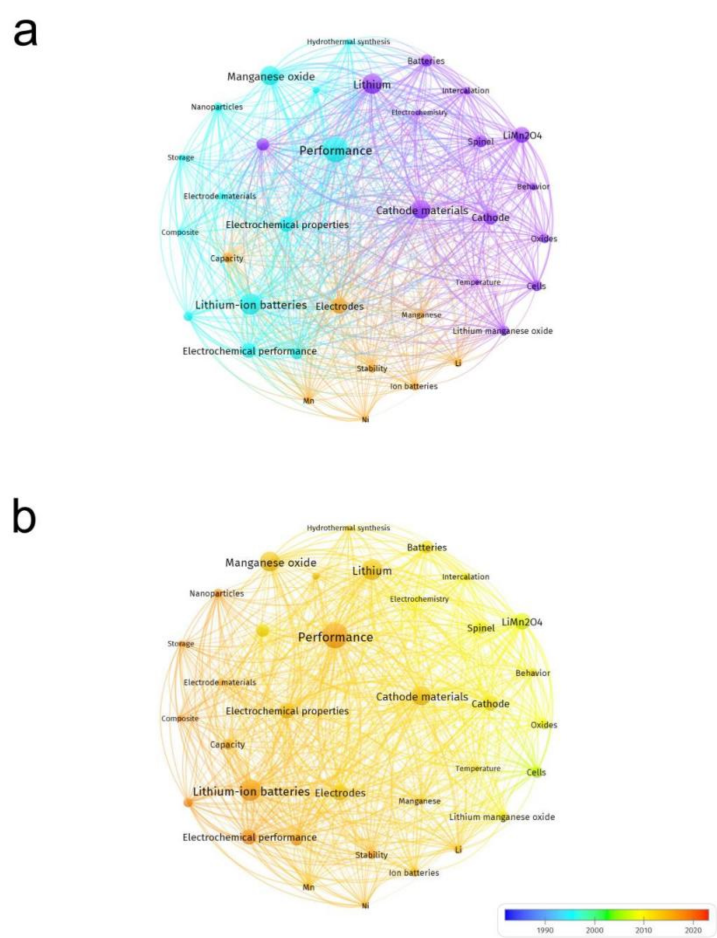

Figure 5. Waste lithium-ion battery recycling keyword contact: (**a**) keyword co-operation relationships and (**b**) keyword clustering analysis.

3.5. Keyword Analysis

3.5.1. Research Hot Topic Analysis

The keywords of the paper can reveal the characteristics and trends of research in the field of waste lithium-ion battery recycling [37–41]. In analysis of keyword co-occurrence and temporal overlay visualization using VOS Viewer (as shown in Figure 5a), node size represents keyword link strength, different colors correspond to the average year of keyword appearance, and the darker the orange represents the later the appearance time.

The development season of catchphrases can mirror the transformative way of examining areas of interest somewhat. As displayed in Figure 5b, the watchwords for the reusing examination of waste lithium-ion batteries have changed from "lithium-particle battery", "manganese oxide", "spinel structure", "button battery", and "electrochemical way of behaving" to "battery execution" and "battery", "energy capacity", "battery limit", "battery soundness", "molecule structure", and so on. The exploration on squander lithium-particle battery reuse has gone through a change from the foundation of an essential hypothesis to designing application and has persistently further developed the specialized, financial, and ecological assessment framework.

To additionally develop the examination content of key hubs, the papers of significant hubs are broken down from top to bottom. Kamioka et al. [42] studied lithium-manganese electrode materials with spinel structure, which were analyzed for the chemical state of manganese ions in nonaqueous electrolyte solutions; Povetkin et al. [43] showed that it is possible to prepare bismuth alloys of indium, lead, and cadmium from trichlate solutions by determining the conditions of electro-crystallization of two-phase alloy-mechanical mixtures; electrochemical alloying of low melting point metals with bismuth plating is conducive to refining the grain structure, smoothing the surface relief and improving its resistance to acid corrosion; Dou et al. [44] explored the synthesis methods, coating, and doping to modification of lithium-rich materials and nanostructured materials of layered lithium–nickel–manganese oxide cathode materials, which can lead to better electrochemical performance. To provide more possibilities for lithium–nickel–manganese oxides as cathode materials for lithium-ion batteries, Lee et al. [45] found that layered lithium–nickel–manganese–cobalt (NMC) oxide systems play an increasing role in the development of advanced rechargeable lithium-ion batteries and that these manganese-rich electrodes offer cost and environmental advantages over nickel electrodes; Brennan et al. [44] reviewed and prospected the products generated in the recycling process of used lithium-ion batteries and used them as adsorbents to play a reducing role in the removal of contaminants, offering the prospect of secondary use of the recovered products.

3.5.2. Analysis of the Evolution of Research Hotspots

Keyword burst discovery recognizes arising patterns in the examination field, mirroring that a point has obtained specific scholastic consideration over a specific timeframe. With the assistance of the developing word capability of CiteSpace programing, a rising examination with a base term of 1 year was performed on the watchwords of the waste lithium-particle battery reuse research from 1984 to 2021, and the main 20 emanant words were chosen and afterward arranged by the length of the new time (Figure 6). The red reach demonstrates the time span with the best change in recurrence of event, i.e., the most persuasive in that time span.

From the emergence intensity, the insertion emergence intensity is the largest (76.5), and the emergence time is 1991, indicating that the field gradually focuses on the development and innovation of material embedding inside the recycling of used lithium-ion batteries. From the time span, dioxide, electrochemistry, spinel, battery-powered lithium battery, and so forth rise out of a more drawn-out time span, showing that the field has been more worried about the exploration on materials and design of waste lithium-particle battery reuse. From the start of the rise, the words simple union, lithium-particle battery, and high limit have effectively arisen, beginning around 2015, which are the popular areas zeroed in on in the field as of late.

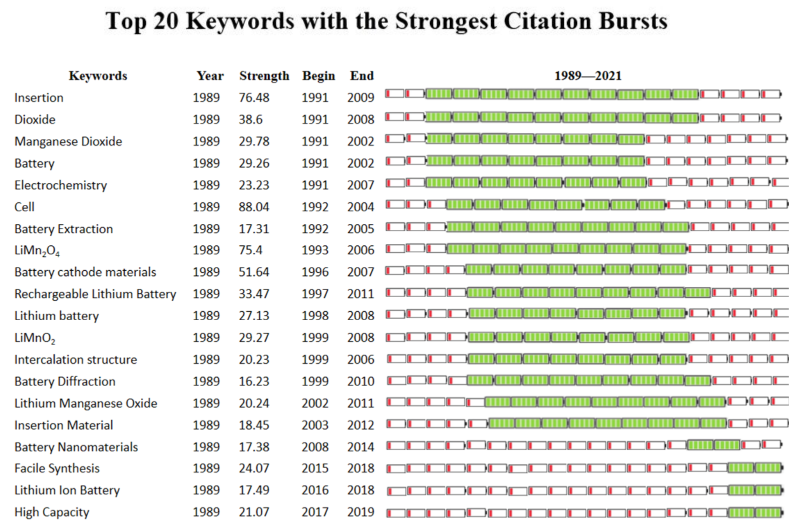

Figure 6. Prominence keyword mapping. Green means: the direction is in hot research, red means: it has relatively reached generalization or is not taken seriously.

4. Conclusions and Future Prospects

In light of the Web of Science center data set, a bibliometric examination of 5487 exploration papers distributed from 1984 to 2021 on spent lithium-particle battery reuse research was directed. The quantity of exploration papers on utilized lithium-particle battery reuse has developed consistently throughout recent years and is, as yet, developing quickly; the innovation has extraordinary potential for advancement and improvement in the following 15 years. Our nation has the most elevated commitment to the quantity of distributions; yet, the quality effect of distributions actually should be worked on through development and the extension of exploration profundity. Considering the enormous capability of waste lithium-particle battery reuse, the high-esteem usage of waste lithium-particle battery reuse results, the improvement of new materials for squander lithium-particle battery reuse, the undetectable commitment to mineral assets, and the assessment of the far-reaching advantages of "assets, climate and economy" will turn into the focal point of exploration and problem areas in the field of waste lithium-particle battery reuse in store for the economical turn of events and extensive advantage upgrade.

In the next research process, we should further grasp the areas of interest to explore and conduct top-down research on the energy reserves of materials, physical and synthetic properties of positive and negative materials, and harmless reuse of ecosystems to make more noise in the world, as well as further strengthen the communication and participation at home and abroad, and enhance the communication among researchers and groups from various disciplines and fields to help better accomplish the goal of reusing used lithium-ion batteries.

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