Energy Storage Ceramics

Subjects: Materials Science, Biomaterials

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Energy storage ceramics are an important material of dielectric capacitors and are among the most discussed topics in the field of energy research. Mainstream energy storage devices include batteries, dielectric capacitors, electrochemical capacitors, and fuel cells. Due to the low dielectric loss and excellent temperature, the status of ceramics is constantly highlighted.

energy storage ceramics | bibliometric | lead-free | microstructure | keywords analysis

1. Introduction

Energy storage ceramics are an important material of dielectric capacitors and are among the most discussed topics in the field of energy research [1]. To our knowledge, the concept of energy storage ceramics has a long history. With the growth in energy demand, the potential applications of energy storage ceramics in the energy-storage area have been excavated. Currently, energy storage ceramics with higher energy densities and lower costs [2][3] are widely used in aerospace [4], military [5], oil drilling [6], and various applications.

Several reviews focus on energy storage ceramics. Researchers have analyzed the progress of sol–gel-derived composite ceramic carbon electrodes [7], ceramic membranes [8], conductivities of solid electrolyte materials in lithium-ion batteries [9], high-temperature sodium batteries [10], lead zirconate-based antiferroelectric materials [11], antiferroelectric ceramics capacitors [12][13], graphene-based materials for supercapacitor electrodes [14], solid-state electrolyte materials [15], lead-free dielectric ceramics [16][17], and high-strain perovskite piezoelectric ceramics [18].

Review papers can synthesize the key theories of a special topic of energy storage ceramics research. Different from review papers, bibliometric methods can analyze massive papers, and show the overall picture of energy storage ceramics research from the perspective of the literature.

Bibliometrics was defined as the “statistical analysis of written publications, such as books or articles” by the OECD [19]. Bibliometric analysis is a statistical evaluation of published papers and academic research [20]. The development of modern bibliometric techniques can be traced back to 1896; Pareto published the first bibliometric paper [21]. More scholars, including Lotka [22], Zipf [23], Bradford [24], and Price [25], have developed new bibliometric methods since then.

Bibliometric analysis provides a perspective that can easily be scaled from the micro- to macrolevel. It has been used to quantitatively analyze academic publications, to show the research status and trends in many research fields, such as health care science services [26][27][28][29][30], computer science [31][32], mechanical engineering [33][34][35][36], psychology [37][38], economics [39][40], energy [41][42], and ecology [43][44][45]. The United Kingdom has considered using bibliometrics in its research excellence framework, to assess the quality of research output [46].

2. Current Research on Energy Storage Ceramics

In total, 3177 papers matched the choice criteria across 10 document types and three publication types. The 10 document types were article (n= 2602), proceedings paper (n= 252), review (n= 213), conference paper (n= 98), editorial material (n= 1), news item (n= 1), and book chapter (n= 1). Including the 3177 papers, there are 105 highly cited papers and five popular papers.

the annual analysis of the published papers. In the last eight years (from 2013 to 2020), the annual publication number has increased rapidly, rising from 83 papers in 2012 to 680 papers in 2020. The increase in the annual publication number since 2013 could be related to the rise in global energy research. It is also worth noting that there has been a steady increase in annual publications since 2008; the average yearly growth rate was 34.9%.

China entered into the field of energy storage ceramics in 2004 and became the leader in 2011. The USA has a long history of energy storage ceramics research and has been the research center for a long time, until being overtaken by China in 2011. India took part in the research of energy storage ceramics earlier than China, but not many papers were published until 2018. The yearly production of the USA and India in recent years is approximately 50 papers.

The publications on energy storage ceramics between 2000 and 2020 were derived from 79 countries/regions. The most productive country/region in the energy storage ceramics research field was China, with a publication share of 55.0% (n= 1747). The USA holds the highest average citations of 47.21 per paper, followed by Australia (ACCP = 46.83) and Canada (ACCP = 42.04). Australia (DC = 95.24%), the UK (DC = 90.73%), and Singapore (DC = 89.74%) are the three countries/regions with the highest percentage of papers cited.

Table 1. Contribution and impact of the top 20 most productive countries/regions in energy storage ceramics research.

Rank	Country/Region	TP	TC	ACCP	DC (%)	h-Index	CC (%)	nCC
1	China	1747	38,872	22.25	86.38	91	19.92	37
2	USA	542	25,586	47.21	88.56	74	39.30	44
3	India	232	3145	13.56	75.00	38	24.57	29
4	Germany	177	4581	25.88	83.62	34	45.20	38
5	UK	151	5002	33.13	90.73	36	72.19	31

Rank	Country/Region	TP	TC	ACCP	DC (%)	h-Index	CC (%)	nCC
6	Japan	132	2355	17.84	84.09	28	46.97	27
7	France	112	1540	13.75	83.93	20	58.93	39
8	South Korea	94	1826	19.43	85.11	24	37.23	12
9	Australia	84	3934	46.83	95.24	26	70.24	17
10	Spain	63	1496	23.75	84.13	19	57.14	27
11	Italy	49	833	17.00	85.71	14	55.10	23
12	Canada	48	2018	42.04	85.42	21	72.92	15
13	Russia	43	668	15.53	83.72	11	65.12	16
14	Poland	42	436	10.38	85.71	14	38.10	13
15	Pakistan	40	441	11.03	70.00	9	77.50	16
16	Singapore	39	1424	36.51	89.74	14	61.54	13
17	Taiwan	28	322	11.50	75.00	10	57.14	10
18	Brazil	26	257	9.88	69.23	7	50.00	9
19	Thailand	24	226	9.42	66.67	9	37.50	9
20	Netherlands	23	434	18.87	86.96	10	73.91	18

Note: TP: total paper; TC: total citations; ACCP: average citations per paper; DC%: percentage of papers cited; CC%: percentage of international collaborations; nCC: number of collaborated countries/regions.

Figure 1 displays country/region collaborations in energy storage ceramics research. Through the collaboration network, the collaboration relationship with different countries/regions can be more intuitively observed, so as to help find more beneficial collaborators. The data near the country/region names are the total number of publications from that country/region. The yellow points in the intersections between the countries/regions illustrate collaborative papers with other countries/regions.

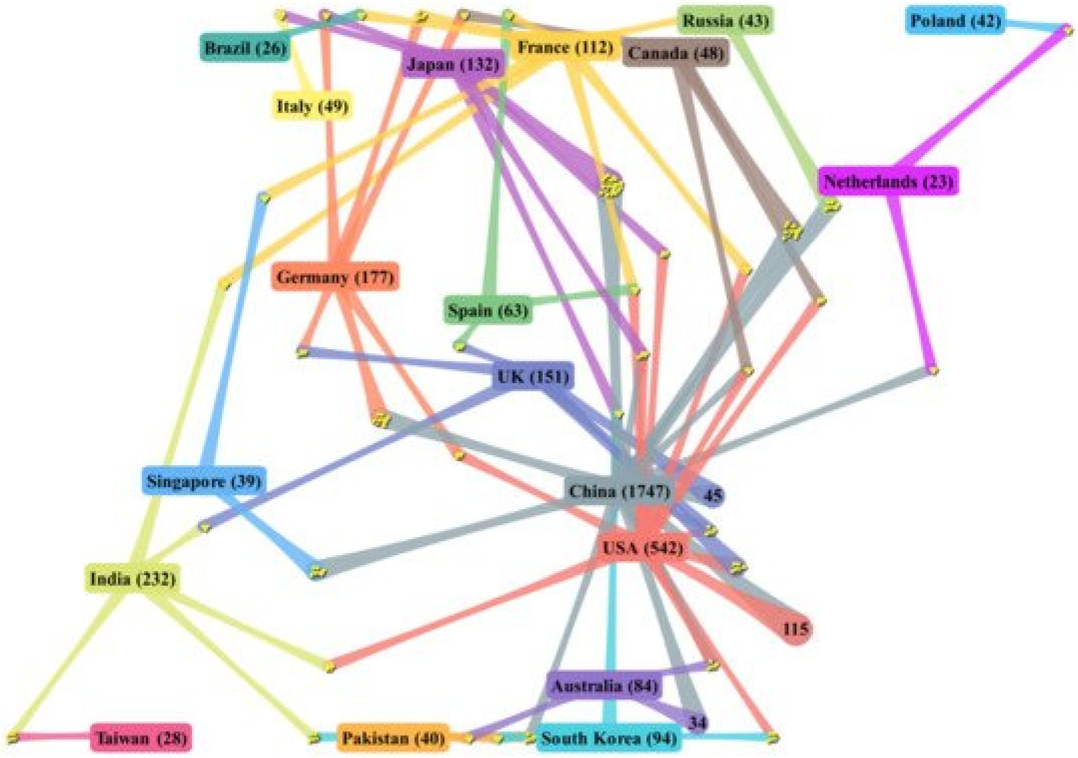

Figure 1. DDA cluster map on collaboration of the top 20 most productive countries/regions.

The figure shows that China is the leader of energy storage ceramics research in cooperation with other countries/regions, followed by the USA, the UK, and Germany. The most productive countries/regions had more frequent cooperation with other countries/regions. Among the top 20 most productive countries/regions, Brazil, Thailand, Italy, and Poland have smaller collaboration networks than the other countries/regions. It is worth mentioning that the USA has the largest number of collaborated countries/regions (nCC = 44), and Pakistan has the highest percentage of international collaborations (CC = 77.50%).

A total of 1816 institutes have participated in energy storage ceramics research. The distribution of institute contributions to publications reiterated the predominance of China in this research field. An Jiao Tong Univ ranks first in terms of total publications, followed by Chinese Acad Sci and Tsinghua Univ. It is worth noting that Penn State Univ (ACCP = 64.90) and Univ Wollongong (ACCP = 54.00) are leading in the table of citations per paper, but a large number of researchers from these institutions are from China.

Additionally, we analyzed the collaborations of energy storage ceramics between the top 30 most productive institutions (see **Figure 2**). Each node represented an institution. The data near the institution names are the total number of publications of the institution. The yellow points in the intersections between the institutions indicate collaborative publications with other institutions in the top 30.

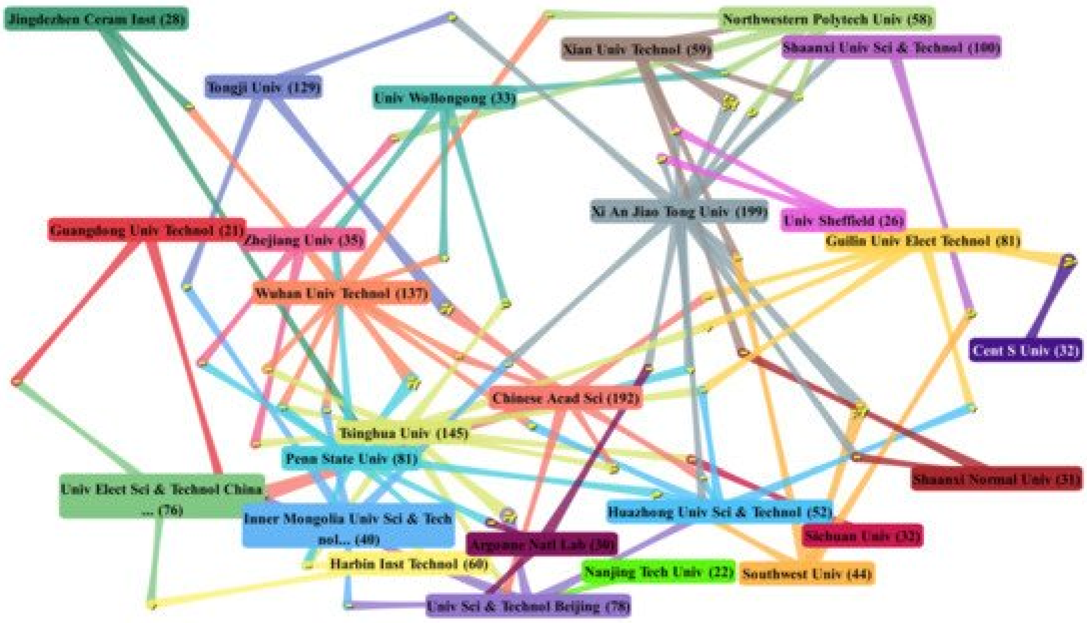

Figure 2. DDA cluster map on collaboration of the top 30 most productive institutions in energy storage ceramics research.

It can be seen that the most productive institutions show more collaboration than other institutions, such as Xi An Jiao Tong Univ, Chinese Acad Sci, Tsinghua Univ, and Wuhan Univ Technol. Among the top 30 most productive institutions, Tsinghua Univ maintains collaboration with more institutions. An Jiao Tong Univ is the most productive institution, with 106 institution collaborations; Xian Univ Technol and Southwest Univ are the main partners. Among the top 30 most productive institutions, Harbin Inst Technol, Sichuan Unive, Natl Univ Singapore, MIT, Natl Inst Technol, Argonne Natl Lab, and German Aerosp Ctr DL have smaller collaboration networks than other institutions.

They contributed the largest number of productive authors. For example, Wuhan Univ Technol has many productive authors, such as H. Hao, H.X. Liu, M.H. Cao, and Z.H. Yao. They co-authored many papers, and the corresponding author of the most papers is H.X. Liu, so H.X. Liu was the representative of these papers. (TP = 86, TC = 2515) is the leader of total productions and citations, followed by H.X. Liu (TP = 73, TC = 2072) and

Three thousand one hundred and seventy-seven papers related to energy storage ceramics research have been published in 88 SCI research areas, among which the top 20 are listed in**Figure 3**. physics—applied (n= 741, 23.33%); and materials science—ceramics (n= 634, 19.96%) are the three research areas with the highest percentage of papers, followed by chemistry—physical (n= 616, 19.40%), and energy and fuels Research from materials science—multidisciplinary; physics—applied; physics—condensed matter; engineering—electrical electronic; and some other research areas are long term, stable, and focus on the research of energy storage ceramics.

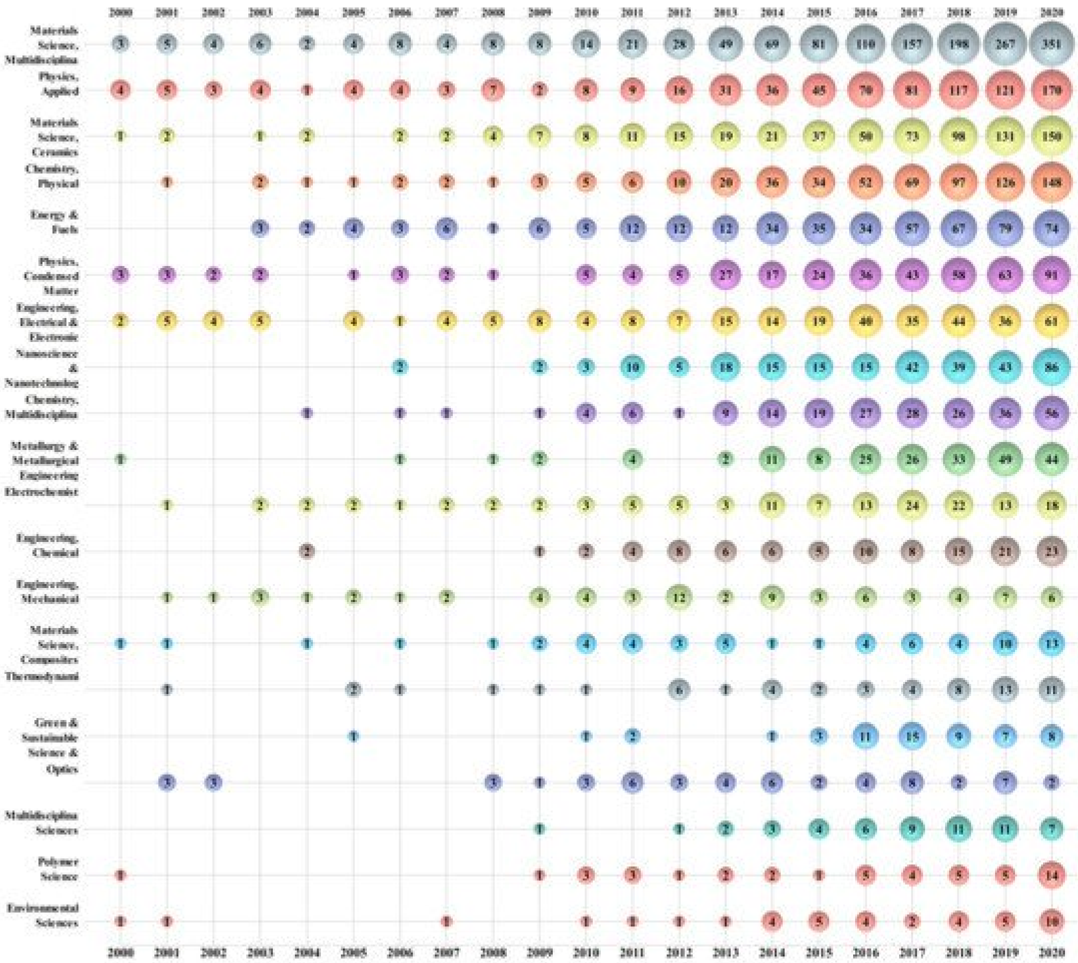

Figure 3. Bubble chart of the top 20 research areas in energy storage ceramics.

In total, 3177 papers were published in 699 publications, with 407 publications publishing only one paper. In **Table 2**, the top 30 most productive journals, in terms of the number of publications, categories, and impact factor 2019, are reported. The top 30 journals have published 1662 papers, which represents 52.31% of the papers in this study. Ceramics Internationalis ranked first (TP: 285, IF2019:

Table 2. Contribution of the top 30 most productive publications in energy storage ceramics research.

Rank	Publication Name	TP	IF2019	Country/Region	Categories
1	Ceramics International	285	3.83	UK	Materials science, ceramics
2	Journal of Materials Science-Materials in Electronics	163	2.22	Netherlands	Physics, condensed matter physics, applied materials science, multidisciplinary engineering, electrical and electronic
3	Journal of Alloys and Compounds	158	4.65	Switzerland	Chemistry, physical metallurgy and metallurgical engineering materials science, multidisciplinary

Rank	Publication Name	TP	IF2019	Country/Region	Categories
4	Journal of the European Ceramic Society	117	4.495	UK	Materials science, ceramics
5	Journal of the American Ceramic Society	108	3.502	USA	Materials science, ceramics
6	Journal of Materials Chemistry A	84	11.301	UK	Energy and fuels chemistry, physical materials science, multidisciplinary
7	ACS Applied Materials and Interfaces	66	8.758	USA	Nanoscience and nanotechnology materials science, multidisciplinary
8	Journal of Materials Chemistry C	60	7.059	UK	Physics, applied materials science, multidisciplinary
9	Journal of Applied Physics	47	2.286	USA	Physics, applied
10	Journal of Power Sources	44	8.247	Netherlands	Energy and fuels chemistry, physical materials science, multidisciplinary electrochemistry
11	Applied Physics Letters	38	3.597	USA	Physics, applied
12	Journal of Materiomics	37	5.797	China Mainland	Chemistry, physical physics, applied materials science, multidisciplinary
13	RSC Advances	37	3.119	UK	Chemistry, multidisciplinary
14	Materials Letters	36	3.204	Netherlands	Physics, applied materials science, multidisciplinary
15	Ferroelectrics	32	0.669	UK	Physics, condensed matter materials science, multidisciplinary
16	International Journal of Hydrogen Energy	32	4.939	UK	Energy and fuels chemistry, physical electrochemistry science
17	Journal of Materials Science	30	3.553	USA	Materials science, multidisciplinary
18	Journal of Electronic Materials	29	1.774	USA	Physics, applied materials science, multidisciplinary engineering, electrical and electronic
19	Materials Research	25	4.019	USA	Materials science, multidisciplinary

Rank	Publication Name	TP	IF2019	Country/Region	Categories
	Bulletin				
20	Journal of Physical Chemistry C	24	4.189	USA	Nanoscience and nanotechnology chemistry, physical materials science, multidisciplinary
21	Materials Research Express	24	1.929	UK	Materials science, multidisciplinary
22	Materials Chemistry and Physics	23	3.408	Switzerland	Materials science, multidisciplinary
23	Advanced Materials	22	27.398	Germany (Fed Rep Ger)	Nanoscience and nanotechnology chemistry, physical physics, condensed matter physics, applied materials science, multidisciplinary chemistry, multidisciplinary
24	Materials	22	3.057	Switzerland	Materials science, multidisciplinary
25	Nano Energy	21	16.602	USA	Nanoscience and nanotechnology chemistry, physical physics, applied materials science, multidisciplinary
26	Advanced Functional Materials	20	16.836	Germany (Fed Rep Ger)	Nanoscience and nanotechnology chemistry, physical physics, condensed matter physics, applied materials science, multidisciplinary chemistry, multidisciplinary
27	Energy and Environmental Science	20	30.289	UK	Energy and fuels engineering, chemical environmental sciences chemistry, multidisciplinary
28	Journal of Advanced Dielectrics	20		Singapore	Physics, applied
29	Advanced Energy Materials	19	25.245	Germany (Fed Rep Ger)	Energy and fuels chemistry, physical physics, condensed matter physics, applied materials science, multidisciplinary
30	Scientific Reports	19	3.998	UK	Multidisciplinary sciences

Note: TP: total paper; IF2019: impact factor 2019.

C(TP: 60, IF2019: 7.059) have grown exponentially in recent years. Research Expresshave declined over time. It is also noteworthy that several journals published papers on energy storage ceramics research during the first 13 years of the 2000s. Since 2013, there have been more publications on energy storage ceramics, indicating that the research area is growing.

Due to some papers' author keywords being missing, here, we used a combination of author keywords and keywords plus to fully reveal this research field. Apart from some of the most commonly used searching keywords, such as “energy storage”, “density”, “ceramics”, “performance”, “energy”, “behavior”, “ferroelectric”, and “dielectric”, the remaining keywords were carefully cleaned. Various expressions of the same subjects, such as “Barium Titanate” and “Batio3”, were merged to ensure that keywords with similar meanings were represented by one unified word. The top 20 cleaned

Figure 4represents a map of energy storage ceramics research. A bubble chart was used to show the development trend of this field in 3D. Using the size of bubble as a third dimension, the chart can be applied to track research frontiers [47]. The number in a bubble represents the frequency of a keyword in that year.

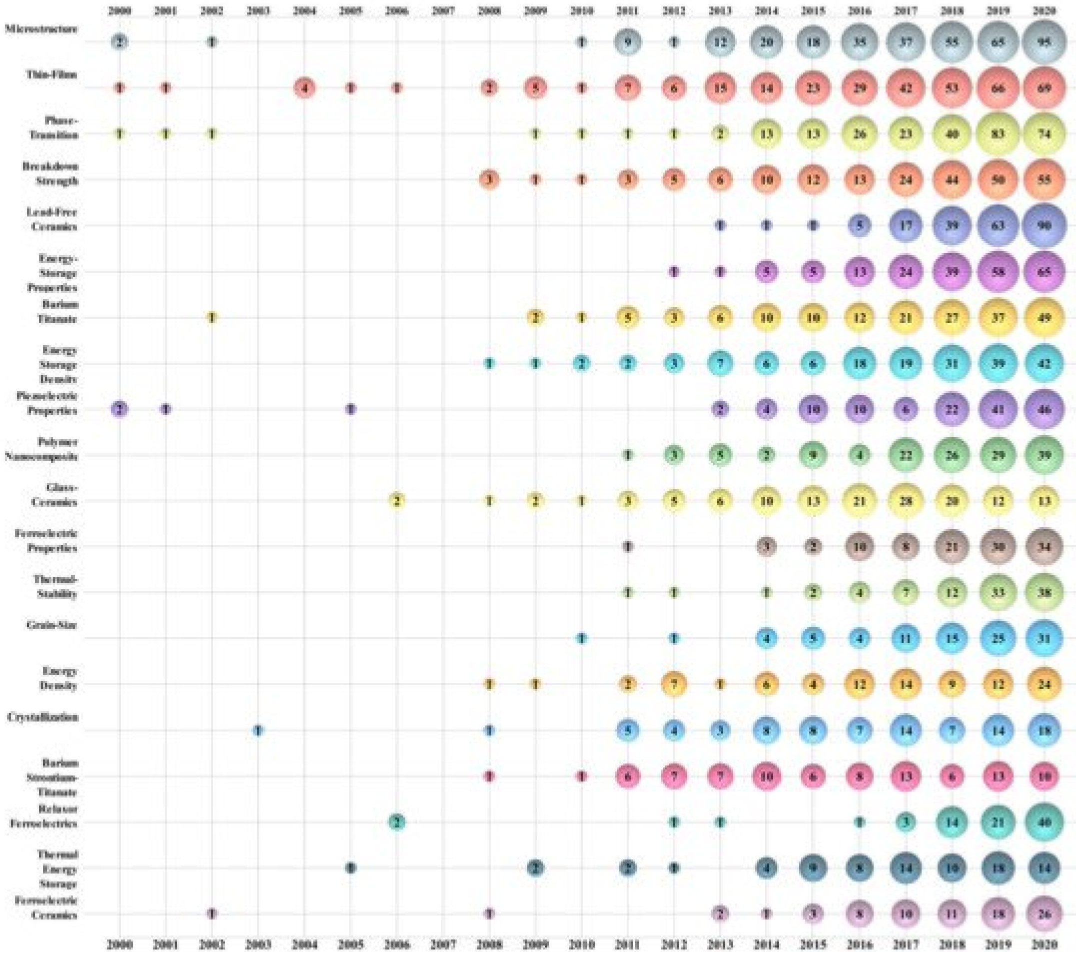

Figure 4. Bubble chart of top 30 keywords of energy storage ceramics research by year.

“Microstructure” (n= 366) ranks first in terms of occurrence, followed by “thin-films” (n= 354) and “phase-transition” (n= 301). The properties, behavior, characteristics, changes, evolution, modification, and design of microstructures were studied by Z.Y. Shen, A.G. Jain, G. Liu, and other researchers [48][49][50]. Thin films, including ferroelectric thin films and antiferroelectric thin films, are a long-term topic of material research for researchers, such as A. Kumar, Q. Li, and B.H. Ma; relevant theories and methods have been constantly updated in recent years With the work of

L. Jin, Q. Xu, R. Xu, and other researchers, related work has made great progress in the past seven years [51][52][53].

It is worth noting that some keywords have become frequent in recent years, such as “lead-free ceramics” (since 2017) and “energy storage performance” (since 2016). In 2017, lead-free ceramics became a popular topic; researchers, such as G. Liu, F. Li, and H.B. Yang, published a large number of papers and promoted the research of energy storage ceramics to the lead-free era [54][55][56]. Almost at the same time, the research of energy storage performance became a frequent appearance in keywords; L. Jin, X. Lu, L. Zhang, and other researchers, carried out a series of exploratory works and advanced the topic rapidly [57][58][59].

The following other keywords can also be noted: the research topic of grain size appeared in 2010 and became a frequent keyword in 2014; the effect, engineering, and dependence of grain size were studied by G. Liu, M.S. Alkathy, G. Chen, and other researchers [60][61]; ferroelectric properties is a topic with a long history, and the number of papers has been increasing since 2014 [62][63]; the production of relaxor ferroelectrics research obviously increased in the last three years; researchers, such as G. Liu, F. Li, and Z. Dai, advanced the research of relaxor ferroelectric behavior, polymers, properties, and transition [64][65].

A review of materials, methods, applications and challenges”—was published byComposites Part B-Engineeringin 2018, and gave an overview of the main 3D printing methods, materials, and their development in trending applications, and the current state of ceramics materials development was presented. A review of materials, methods, applications and challenges”—is ranked first in the field of total citations per year. The USA contributed eleven of them, followed by China (2), Switzerland (1), UK (1), Australia (1), Israel (1), Germany (1), Spain (1), and India (1), which indicated that the USA was the leading country of academic influence in this research field. It is worth noting that many papers are the results of multidisciplinary integration.

Researchers usually identify the most interesting recent research topics within a research field with popular ESI papers. There were five popular ESI papers in this field, all of which were published in 2019 (**Table 3**). Three of them are review papers, and two of them are article papers.

Table 3. Popular ESI papers in energy storage ceramics research field.

No.	Authors	Article Title	TC	Source	Type	Year
1	L.T. Yang et al.	Perovskite lead-free dielectrics for energy storage applications	196	Prog. Mater. Sci.	Review	2019
2	H. Luo et al.	Interface design for high energy density polymer nanocomposites	124	Chem. Soc. Rev.	Review	2019
3	H. Qi et al.	Linear-like lead-free relaxor antiferroelectric $(Bi_{0.5}Na_{0.5})TiO_3$-$NaNbO_3$ with giant energy-storage density/efficiency and super stability against temperature and frequency	106	J. Mater. Chem. A	Article	2019

No.	Authors	Article Title	TC	Source	Type	Year
4	W.G. Ma et al.	Enhanced energy-storage performance with excellent stability under low electric fields in BNT-ST relaxor ferroelectric ceramics	91	J. Mater. Chem. C	Article	2019
5	A.J. Samson, et al.	A bird's-eye view of Li-stuffed garnet-type $Li_7La_3Zr_2O_{12}$ ceramic electrolytes for advanced all-solid-state Li batteries	64	Energy Environ. Sci.	Review	2019

Note: TC: total citations; Type: document type.

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