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Scientometric Analysis of Lithium-Ion Batteries Research Literature

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ABSTRACT

Lithium-ion batteries are now one of the best ways for preserving energy because they have a high energy density, a long cycle life, and are very efficient. They are widely used in portable electronics, electric cars, and systems that use renewable energy, which helps the world move toward more sustainable energy. During charging and discharging, Lithium-ion batteries work by moving lithium ions back and forth between the anode and cathode. The study examines Indian and international publications on water resources between 1998 and 2022, evaluating the papers and identifying trends using scientometrics methodologies. Web of Science found a total of 2388 research papers contributed by Indian scientists and 74126 research papers contributed by world researchers, a bibliographical and citation database offered by Clarivate Analytics that provides access to the best literature. It also evaluates the effectiveness of other scientometric metrics, including publications, citations, relative growth rate, doubling time, activity index, and collaboration. India has experienced exponential growth in its lithium-ion battery during the past 25 years..

KEYWORDS: Lithium-ion batteries, Scientometrics, relative growth rate, doubling time, activity index,

1. INTRODUCTION

Lithium-ion batteries are one of the most important new technologies for storing energy. They are very important for modern portable electronics, electric cars, and renewable energy systems. Lithium-ion batteries are a type of rechargeable battery that works by moving lithium ions back and forth between the anode and cathode during charge and discharge cycles. This makes it possible to store and release energy efficiently. The increasing global need for clean and long-lasting energy sources helped speed up research and development in lithium-ion battery technology. Compared to lead-acid and nickel-based batteries, they are better because they have a high energy density, a long cycle life, are light, and have a low self-discharge rate. These traits have made them very popular for use in everything from smartphones and laptops to electric cars and large-scale energy storage systems.

The basic idea behind how a lithium-ion battery works is that lithium ions move back and forth between two electrodes, the anode and the cathode, through an electrolyte medium. When charging, lithium ions move from the cathode to the anode, where they are stored. When discharging, they move back to the cathode, releasing energy that powers electronic devices. This electrochemical mechanism makes it possible to store energy in a way that is both efficient and repeatable. This makes Lithium-ion batteries great for many different uses. A standard lithium-ion battery has four main parts: a cathode (usually made of lithium metal oxides like lithium cobalt oxide, lithium iron phosphate, or lithium nickel manganese cobalt oxide), an anode (usually made of graphite or other carbon-based materials), an electrolyte (a lithium salt dissolved in an organic solvent), and a separator that keeps the electrodes from touching each other directly while letting ions flow. The choice and optimisation of these materials have a big effect on the battery's performance, safety, and how long it lasts.

Research into lithium-ion battery technology is speeding up a lot because more and more people around the world want clean, sustainable energy. The increasing use of electric vehicles (EVs) and the growth of renewable energy systems like solar and wind power have made the need for efficient, scalable, and reliable energy storage solutions even greater. Lithium-ion batteries are very important for making renewable energy sources more reliable by allowing energy to be stored and the grid to be stabilised. Even though lithium-ion batteries are very popular, they have many technical, economic, and environmental challenges. Safety issues such as thermal runaway and fire hazards remain significant, especially in high-power battery systems. Also, the fact that lithium, cobalt, and nickel are rare and expensive raw materials makes people worry about how available they are, how much they cost, and how they affect the environment. Recycling and throwing away used batteries also pose big problems for sustainability that need good solutions.

Lithium-ion batteries have some technical, financial, and environmental issues despite their widespread popularity. Particularly with high-capacity battery systems, safety considerations like thermal runaway and fire risks continue to be crucial. Concerns regarding resource availability, pricing volatility, and environmental effect are further raised by the dependence on costly and rare raw minerals like nickel, cobalt, and lithium. Used battery recycling and disposal pose serious environmental issues that need for practical solutions. Ongoing research efforts are concentrated on enhancing battery performance, safety, and sustainability in response to these issues. In order to improve energy density and lower hazards, new battery topologies, solid-state electrolytes, and next-generation electrode materials have been developed as a result of advancements in material science. Additionally, other energy storage technologies, including solid-state and sodium-ion batteries, are being investigated as possible substitutes or enhancements to traditional lithium-ion systems.

2. OBJECTIVES OF THE STUDY

The main objectives of the study are to present the growth and progress of lithium-ion batteries research during 1998 to 2022, as per the Web of Science database and make a quantitative and qualitative assessment by way of analysing various features of research such as

- ❖ The study aims to analyse the year-wise growth pattern of lithium-ion batteries research in India and the world from 1998 to 2022.
- ❖ To identify the relative growth rate and doubling time of publications in lithium-ion batteries research.
- ❖ To identify the relative growth rate and doubling time of citations in lithium-ion batteries research.
- ❖ To study the Exponential Growth Rate and Annual Growth Rate in lithium-ion batteries research.

- To examine the Activity Index and Publication Efficiency Index in lithium-ion batteries research.
- To analyse the time-series data on lithium-ion battery research publications.
- To find out the forms of communication used by the researcher in lithium-ion batteries research.
- To identify the top fifteen authors, journals, and highly cited articles in lithium-ion batteries research.

3. METHODOLOGY

The research scope was defined as lithium-ion batteries. The search filters were defined to enable a search of articles from the Web of Science Core Collection, comprising over 21,100 peer-reviewed journals, books, and conference proceedings across more than 250 subject areas in sciences, social sciences, and arts & humanities. The search strategy was ((TS= lithium-ion batteries*)), ensuring a comprehensive approach to data collection.

4. DATA ANALYSIS AND INTERPRETATION

4.1 Lithium-Ion Batteries Research in India's Context:

Analysis of Record & Citation-Wise: Table 1 shows India's research output in lithium-ion batteries from 1998 to 2022. A total of 2388 records were published during 1998-2022 on lithium-ion batteries covered in the Web of Science database. The year 2022 is the most productive year with 377 (15.79%), and the least productive year is 2000 with 2 documents (0.08%). A total of 71084 citations were received during 1998-2022. The year 2018 is the most cited year with 7413 citations received, and the least productive year is 2000 with 93 citations received.

Analysis of Average Citation Per Paper in India: As per the table, India's lithium-ion batteries received the highest citation per paper in 2011, receiving 70.74 average citations per paper and the lowest average citation per paper was received by the year 2022, with 9.77 citations.

Analysis of H-Index Based: Among the most productive year-wise h-indexes in the year 2018 received was 46, and the lowest h-index received in the years 1998 and 2000 was 2.

Lithium-Ion Batteries Research in the World Context:

Analysis of Record & Citation-Wise: Data presented in Table 1 shows the world research output on lithium-ion batteries from 1998 to 2022. A total of 74216 records were published during 1998-2022 on lithium-ion batteries covered in the Web of Science database. The year 2022 is the most productive year with 9115 (12.28%), and the least productive year is 1998 with 149 documents (0.20%). A total of 3545729 citations were received during 1998-2022. The year 2018 is the most cited year with 337523 citations received, and the least productive year is 1998 with 13822 citations received.

Analysis of Average Citation Per Paper of the World: As per the table, the World lithium-ion batteries received the highest citation per paper in 2001 received 129.66 average citations per paper and the lowest average citation per paper was received by the year 2022, with 9.91 citations.

Analysis of H-Index Based: Among the most productive year-wise h-index in the year 2017 received 230 h-index and the lowest h-index received in the years 1998 and 1998 was 54.

Table 1: Year-Wise Research Publications of Lithium-Ion Batteries Research: India V/s World

India						World					
Year	**TP**	**%**	**TC**	**ACCP**	**H-Index**	**Year**	**TP**	**%**	**TC**	**ACCP**	**H-Index**
1998	3	0.13	126	42	2	1998	149	0.2	13822	92.77	54
1999	5	0.21	346	69.2	4	1999	211	0.28	19027	90.18	70
2000	2	0.08	93	46.5	2	2000	245	0.33	22678	92.56	66
2001	8	0.34	240	30	6	2001	310	0.42	40195	129.66	78
2002	8	0.34	240	30	6	2002	349	0.47	24582	70.44	86
2003	4	0.17	103	25.75	3	2003	419	0.56	27736	66.2	91
2004	10	0.42	440	44	6	2004	412	0.56	27498	66.74	93
2005	8	0.34	426	53.25	6	2005	533	0.72	47610	89.32	103
2006	25	1.05	1649	65.96	17	2006	655	0.88	47848	73.05	106
2007	28	1.17	858	30.64	18	2007	725	0.98	51833	71.49	110
2008	22	0.92	697	31.68	14	2008	730	0.98	58502	80.14	113
2009	18	0.75	693	38.5	12	2009	933	1.26	71330	76.45	134
2010	24	1.01	707	29.46	14	2010	1157	1.56	122143	105.57	171
2011	39	1.63	2759	70.74	21	2011	1747	2.35	181187	103.71	202
2012	55	2.3	2616	47.56	23	2012	2370	3.19	203801	85.99	208
2013	73	3.06	4508	61.75	31	2013	3322	4.48	243577	73.32	216
2014	101	4.23	5489	54.35	39	2014	4266	5.75	280198	65.68	219
2015	118	4.94	6881	58.31	42	2015	4704	6.34	286580	60.92	212
2016	164	6.87	4609	28.1	35	2016	5330	7.18	286549	53.76	207
2017	225	9.42	7237	32.16	44	2017	6314	8.51	337251	53.41	230
2018	237	9.92	7413	31.28	46	2018	6726	9.06	337523	50.18	220
2019	233	9.76	6847	29.39	42	2019	7182	9.68	287065	39.97	194
2020	266	11.14	6573	24.71	45	2020	7519	10.13	249373	33.17	175
2021	335	14.03	5851	17.47	37	2021	8793	11.85	187508	21.32	132
2022	377	15.79	3683	9.77	28	2022	9115	12.28	90313	9.91	78
Total	**2388**	**100**	**71084**				**74216**	**100**	**3545729**		

TP= Total Publications, %= Percentage, TC= Total Citations, ACPP= Average Citation Per Paper, %= Percentage. NA = Not Available.

4.2 Relative Growth Rate and Doubling Time of Publication

Relative Growth Rate of India's Publications: Table 2 shows the relative growth rate and doubling time of India's lithium-ion batteries research output during the sample period of 1998-2022, from 0.98 to 0.17. The highest relative growth rate of 0.98 was found in the year 1999, and the lowest relative growth rate was found in the years 2003 and 2009 (0.14). It is observed that the relative growth rate of lithium-ion batteries research output shows a decreasing trend. The overall mean relative growth rate of the lithium-ion batteries was 0.27 in the study period.

Doubling Time of India's Publications: The doubling time of lithium-ion batteries research literature output showed an increasing trend. Doubling Time increases from 0.71 in the year 1999 to 4.03 in the year 2022. The highest doubling time of 5.07 was found in the year 2009, and the lowest doubling time was found at 0.71 in the year 1999. The overall mean doubling time of the lithium-ion batteries was 2.92 in the study period.

Relative Growth Rate of World's Publications: Table 2 shows the relative growth rate and doubling time of world lithium-ion batteries research output during the sample period of 1998-2022, from 0.88 to 0.13. The highest relative growth rate of 0.88 was found in the year 1999, and the lowest relative growth rate was found in the year 2022 (0.13). It is observed that the relative growth rate of lithium-ion batteries research output shows a decreasing trend. The overall mean relative growth rate of the lithium-ion batteries was 0.25 in the study period.

Doubling Time of World's Publications: The doubling time of lithium-ion batteries research literature output showed an increasing trend. Doubling Time increases from 0.79 in the year 1999 to 5.29 in the year 2022. The highest doubling time of 5.29 was found in the year 2022, and the lowest doubling time was found at 0.79 in the year 1999. The overall mean doubling time of the lithium-ion batteries was 3.08 in the study period.

Table 2: Relative Growth Rate and Doubling Time of Publication in Lithium-Ion Batteries Research: India v/s World

India							World					
Year	**TP**	**Cum**	**Log 1**	**Log 2**	**RGR**	**Dt**	**TP**	**Cum**	**Log 1**	**Log 2**	**RGR**	**Dt**
1998	3	3		1.1			149	149		5		
1999	5	8	1.1	2.08	0.98	0.71	211	360	5	5.89	0.88	0.79
2000	2	10	2.08	2.3	0.22	3.11	245	605	5.89	6.41	0.52	1.33
2001	8	18	2.3	2.89	0.59	1.18	310	915	6.41	6.82	0.41	1.68
2002	8	26	2.89	3.26	0.37	1.88	349	1264	6.82	7.14	0.32	2.14
2003	4	30	3.26	3.4	0.14	4.84	419	1683	7.14	7.43	0.29	2.42
2004	10	40	3.4	3.69	0.29	2.41	412	2095	7.43	7.65	0.22	3.16
2005	8	48	3.69	3.87	0.18	3.8	533	2628	7.65	7.87	0.23	3.06
2006	25	73	3.87	4.29	0.42	1.65	655	3283	7.87	8.1	0.22	3.11
2007	28	101	4.29	4.62	0.32	2.13	725	4008	8.1	8.3	0.2	3.47
2008	22	123	4.62	4.81	0.2	3.52	730	4738	8.3	8.46	0.17	4.14
2009	18	141	4.81	4.95	0.14	5.07	933	5671	8.46	8.64	0.18	3.86
2010	24	165	4.95	5.11	0.16	4.41	1157	6828	8.64	8.83	0.19	3.73
2011	39	204	5.11	5.32	0.21	3.27	1747	8575	8.83	9.06	0.23	3.04
2012	55	259	5.32	5.56	0.24	2.9	2370	10945	9.06	9.3	0.24	2.84
2013	73	332	5.56	5.81	0.25	2.79	3322	14267	9.3	9.57	0.27	2.61
2014	101	433	5.81	6.07	0.27	2.61	4266	18533	9.57	9.83	0.26	2.65
2015	118	551	6.07	6.31	0.24	2.88	4704	23237	9.83	10.05	0.23	3.06
2016	164	715	6.31	6.57	0.26	2.66	5330	28567	10.05	10.26	0.21	3.36
2017	225	940	6.57	6.85	0.27	2.53	6314	34881	10.26	10.46	0.2	3.47

2018	237	1177	6.85	7.07	0.22	3.08	6726	41607	10.46	10.64	0.18	3.93
2019	233	1410	7.07	7.25	0.18	3.84	7182	48789	10.64	10.8	0.16	4.35
2020	266	1676	7.25	7.42	0.17	4.01	7519	56308	10.8	10.94	0.14	4.83
2021	335	2011	7.42	7.61	0.18	3.8	8793	65101	10.94	11.08	0.15	4.78
2022	377	2388	7.61	7.78	0.17	4.03	9115	74216	11.08	11.21	0.13	5.29
Total	**2388**	**Mean value**			**0.27**	**2.92**	**74216**	**Mean value**			**0.25**	**3.08**

TP = Total Publication, Cum=Cumulative, RGR= Relative Growth Rate, Dt= Doubling Time.

4.3 Relative Growth Rate and Doubling Time of Citations

Relative Growth Rate of India's Citations: Table 3 show the relative growth rate and doubling time of India's lithium-ion batteries research output during the sample period of 1998-2022, from 1.32 to 0.05. The highest relative growth rate of 1.32 was found in the year 1999, and the lowest relative growth rate was found in the year 2022 (0.05). It is observed that the relative growth rate of lithium-ion batteries research output shows a decreasing trend. The overall mean relative growth rate of the lithium-ion batteries was 0.25 in the study period.

Doubling Time of India's Citation: The doubling time of lithium-ion batteries research literature output showed an increasing trend. Doubling Time increases from 0.52 in the year 1999 to 13.03 in the year 2022. The highest doubling time of 13.03 was found in the year 2022, and the lowest doubling time was found at 0.52 in the year 1999. The overall mean doubling time of the lithium-ion batteries was 3.95 in the study period.

Relative Growth Rate of World's Citations: Table 3 show the relative growth rate and doubling time of world lithium-ion batteries research output during the sample period of 1998-2022, from 0.87 to 0.03. The highest relative growth rate of 0.87 was found in the year 1999, and the lowest relative growth rate was found in the year 2022 (0.03). It is observed that the relative growth rate of lithium-ion batteries research output shows a decreasing trend. The overall mean relative growth rate of the lithium-ion batteries was 0.22 in the study period.

Doubling Time of World's Citations: The doubling time of lithium-ion batteries research literature output showed an increasing trend. Doubling Time increases from 0.80 in the year 1999 to 26.86 in the year 2022. The highest doubling time of 26.86 was found in the year 2022, and the lowest doubling time was found at 0.80 in the year 1999. The overall mean doubling time of the lithium-ion batteries was 4.82 in the study period.

Table 3: Relative Growth Rate and Doubling Time of Citation in Lithium-Ion Batteries Research

India							World					
Year	**TC**	**Cum**	**Log 1**	**Log 2**	**RGR**	**Dt**	**TC**	**Cum**	**Log 1**	**Log 2**	**RGR**	**Dt**
1998	126	126		4.84			13822	13822		9.53		
1999	346	472	4.84	6.16	1.32	0.52	19027	32849	9.53	10.4	0.87	0.8
2000	93	565	6.16	6.34	0.18	3.85	22678	55527	10.4	10.92	0.52	1.32
2001	240	805	6.34	6.69	0.35	1.96	40195	95722	10.92	11.47	0.54	1.27
2002	240	1045	6.69	6.95	0.26	2.66	24582	120304	11.47	11.7	0.23	3.03
2003	103	1148	6.95	7.05	0.09	7.37	27736	148040	11.7	11.91	0.21	3.34
2004	440	1588	7.05	7.37	0.32	2.14	27498	175538	11.91	12.08	0.17	4.07

2005	426	2014	7.37	7.61	0.24	2.92	47610	223148	12.08	12.32	0.24	2.89
2006	1649	3663	7.61	8.21	0.6	1.16	47848	270996	12.32	12.51	0.19	3.57
2007	858	4521	8.21	8.42	0.21	3.29	51833	322829	12.51	12.68	0.18	3.96
2008	697	5218	8.42	8.56	0.14	4.83	58502	381331	12.68	12.85	0.17	4.16
2009	693	5911	8.56	8.68	0.12	5.56	71330	452661	12.85	13.02	0.17	4.04
2010	707	6618	8.68	8.8	0.11	6.13	122143	574804	13.02	13.26	0.24	2.9
2011	2759	9377	8.8	9.15	0.35	1.99	181187	755991	13.26	13.54	0.27	2.53
2012	2616	11993	9.15	9.39	0.25	2.82	203801	959792	13.54	13.77	0.24	2.9
2013	4508	16501	9.39	9.71	0.32	2.17	243577	1203369	13.77	14	0.23	3.06
2014	5489	21990	9.71	10	0.29	2.41	280198	1483567	14	14.21	0.21	3.31
2015	6881	28871	10	10.27	0.27	2.55	286580	1770147	14.21	14.39	0.18	3.92
2016	4609	33480	10.27	10.42	0.15	4.68	286549	2056696	14.39	14.54	0.15	4.62
2017	7237	40717	10.42	10.61	0.2	3.54	337251	2393947	14.54	14.69	0.15	4.56
2018	7413	48130	10.61	10.78	0.17	4.14	337523	2731470	14.69	14.82	0.13	5.25
2019	6847	54977	10.78	10.91	0.13	5.21	287065	3018535	14.82	14.92	0.1	6.93
2020	6573	61550	10.91	11.03	0.11	6.14	249373	3267908	14.92	15	0.08	8.73
2021	5851	67401	11.03	11.12	0.09	7.63	187508	3455416	15	15.06	0.06	12.42
2022	3683	71084	11.12	11.17	0.05	13.03	90313	3545729	15.06	15.08	0.03	26.86
Total	**71084**	**Mean Value**			**0.25**	**3.95**	**3545729**	**Mean Value**			**0.22**	**4.82**

TC = Total Citations, Cum=Cumulative, RGR = Relative Growth Rate, Dt = Doubling Time.

4.4 Annual Growth Rate

Table 4 depicts the annual growth rate of publications calculated during the study period 1998- 2022 in the research field of lithium-ion battery in which a total of 2388 related documents were published. There is a fluctuation in the annual growth rate during the period of study. The highest growth rate was recorded at 300 in the year 2001, and the lowest growth rate was recorded at zero in the year 1998. The years 2000, 2003, 2005, 2008, 2009 and 2019 received negative AGR scores, and the remaining years received positive growth rates in the sample period.

Table 4: Annual Growth Rate of Lithium-Ion Batteries Research

Year	TP	Cum	AGR
1998	3	3	0
1999	5	8	66.67
2000	2	10	-60
2001	8	18	300
2002	8	26	0
2003	4	30	-50
2004	10	40	150
2005	8	48	-20
2006	25	73	212.5

2007	28	101	12
2008	22	123	-21.43
2009	18	141	-18.18
2010	24	165	33.33
2011	39	204	62.5
2012	55	259	41.03
2013	73	332	32.73
2014	101	433	38.36
2015	118	551	16.83
2016	164	715	38.98
2017	225	940	37.2
2018	237	1177	5.33
2019	233	1410	-1.69
2020	266	1676	14.16
2021	335	2011	25.94
2022	377	2388	12.54
Total	**2388**		

TP= Total Publication, Cum= Cumulative, AGR= Annual Growth Rate

4.5 Activity Index

Table 5 shows the activity index of India's contribution witnessed in World output in lithium-ion batteries research from 1998 to 2022. The data reveals that the activity index for 17 years out of 25 years of study is less than 100, which reflects the lower activity of lithium-ion batteries research output in the literature of the World's average. The highest activity index was 128.54 observed for the year 2022, with the next highest value of 120.03 in the year 2007. The activity index at a very low level in the year 2000 was 25.37 for the overall study period.

Table 5: Activity Index of Lithium-Ion Batteries Research

Year	World TP	India TP	AI
1998	149	3	62.57
1999	211	5	73.65
2000	245	2	25.37
2001	310	8	80.2
2002	349	8	71.24
2003	419	4	29.67
2004	412	10	75.43
2005	533	8	46.65
2006	655	25	118.62
2007	725	28	120.03
2008	730	22	93.66

2009	933	18	59.96
2010	1157	24	64.47
2011	1747	39	69.38
2012	2370	55	72.12
2013	3322	73	68.29
2014	4266	101	73.58
2015	4704	118	77.96
2016	5330	164	95.63
2017	6314	225	110.75
2018	6726	237	109.51
2019	7182	233	100.83
2020	7519	266	109.95
2021	8793	335	118.41
2022	9115	377	128.54
Total	**74216**	**2388**	

TP = Total Publication, AI = Activity Index.

4.6 Exponential Growth Rate

Table 6 reveals the exponential growth rate of overall publications on Indian lithium-ion battery research output during the study period. The average exponential growth rate is 1.33 during the sample period. The highest growth rate was found at 4.00 in the year 2001 with 8 publications, and the lowest exponential growth rate was recorded at 0.40 with 2 publications in the year 2000.

Table 6: Exponential Growth Rate of Lithium-Ion Batteries Research

Year	TP	EGR
1998	3	
1999	5	1.67
2000	2	0.4
2001	8	4
2002	8	1
2003	4	0.5
2004	10	2.5
2005	8	0.8
2006	25	3.13
2007	28	1.12
2008	22	0.79
2009	18	0.82
2010	24	1.33
2011	39	1.63
2012	55	1.41

2013	73	1.33
2014	101	1.38
2015	118	1.17
2016	164	1.39
2017	225	1.37
2018	237	1.05
2019	233	0.98
2020	266	1.14
2021	335	1.26
2022	377	1.13
Total	**2388**	**1.33**

TP = Total Publication, EGR = Exponential Growth Rate

4.7 Exponential Growth Rate

Table 7 reveals the publication efficiency index of overall publications on Indian lithium-ion batteries research output during the study period. The average exponential growth rate is 1.35 during the sample period. The highest growth rate was found at 2.38 in the year 2011, with 39 publications, and the lowest publication efficiency index was recorded at 0.33 with 377 publications in the year 2022.

Table 7: Publication Efficiency Index of Lithium-Ion Batteries Research

Year	TP	TC	PEI
1998	3	126	1.41
1999	5	346	2.32
2000	2	93	1.56
2001	8	240	1.01
2002	8	240	1.01
2003	4	103	0.87
2004	10	440	1.48
2005	8	426	1.79
2006	25	1649	2.22
2007	28	858	1.03
2008	22	697	1.06
2009	18	693	1.29
2010	24	707	0.99
2011	39	2759	2.38
2012	55	2616	1.60
2013	73	4508	2.07
2014	101	5489	1.83
2015	118	6881	1.96

2016	164	4609	0.94
2017	225	7237	1.08
2018	237	7413	1.05
2019	233	6847	0.99
2020	266	6573	0.83
2021	335	5851	0.59
2022	377	3683	0.33
Total	**2388**	**71084**	**1.35**

TP= Total Publications, %= Percentage, TC= Total Citations, PEI = Publication Efficiency Index

4.8 Future Growth Trend (Time Series Analysis)

Time Series Analysis is used to estimate the productivity of publications in the future. In this study, this technique is used to estimate the literature output for the years 2027, 2032,2040 and 2050.

Table 8 shows the time series data for the lithium-ion batteries research output from 1998 to 2022. The formula was used to calculate the Straight Line equation model below mentioned that,

Straight Line equation $Yc = a + bX$ Since $\Sigma X = 0$

Y- Publications

X- Unit of time

a & b constants to be calculated

Since $\sum X = 0$

$a = \Sigma Y/N = 2388/25 = 95.52$

$b = \Sigma XY/\Sigma X2 = 19404/1300 = 14.93$

Estimated literature in 2027 =95.52+(14.93*(2027-2010)= 349.26

Estimated literature in 2032 = 95.52+(14.93*(2032-2010)= 423.90

Estimated literature in 2040 =95.52+(14.93*(2040-2010)= 543.30

Estimated literature in 2050 = 95.52+(14.93*(2050-2010)= 692.57

"Therefore, the predicted lithium-ion batteries research output for the years 2027,2032,2040 and 2050 is 349.26, 423.90, 543.30 and 692.57, respectively."

Table 8: Future Growth Trend (Time Series Analysis) of Lithium-Ion Batteries Research

Year	TP	X	X2	XY
1998	3	-12	144	36
1999	5	-11	121	55
2000	2	-10	100	20
2001	8	-9	81	72
2002	8	-8	64	64
2003	4	-7	49	28
2004	10	-6	36	60

2005	8	-5	25	40
2006	25	-4	16	100
2007	28	-3	9	84
2008	22	-2	4	44
2009	18	-1	1	18
2010	24	0	0	0
2011	39	1	1	39
2012	55	2	4	110
2013	73	3	9	219
2014	101	4	16	404
2015	118	5	25	590
2016	164	6	36	984
2017	225	7	49	1575
2018	237	8	64	1896
2019	233	9	81	2097
2020	266	10	100	2660
2021	335	11	121	3685
2022	377	12	144	4524
Total	**2388**		**1300**	**19404**

TP= Total Publications

4.9 Average Author Per Paper and Productivity Per Author

Average Author Per Paper: Table 9 depicts the data pertaining to author productivity and average author per paper in the field of lithium-ion batteries research. It is revealed from Table 6 that the average number of authors per article is 4.24 for 2388 articles published with 10753 authors together contribution for the period 1998-2022. It is also clear from the table that the highest average number of authors per article is 5.00, with 25 authors for 5 records in the year 1999, and the lowest average number of authors per paper was 3.39, with 95 authors for 28 records in the year 2007.

Productivity Per Author: The average productivity per author for the period 1998-2022 is 0.24. The highest number of author productivity was found in the years 2000, 2007 and 2010, i.e. 0.29. The minimum number of authors' productivity noted was 0.20, with 5 publications and 225 authors in the year 1999.

Table 9: Average Author Per Paper and Productivity Per Author of Lithium-Ion Batteries Research

Year	TP	TA	AAPP	PPA
1998	3	14	4.67	0.21
1999	5	25	5	0.2
2000	2	7	3.5	0.29
2001	8	36	4.5	0.22
2002	8	29	3.63	0.28

2003	4	15	3.75	0.27
2004	10	40	4	0.25
2005	8	34	4.25	0.24
2006	25	108	4.32	0.23
2007	28	95	3.39	0.29
2008	22	88	4	0.25
2009	18	81	4.5	0.22
2010	24	84	3.5	0.29
2011	39	153	3.92	0.25
2012	55	231	4.2	0.24
2013	73	317	4.34	0.23
2014	101	419	4.15	0.24
2015	118	515	4.36	0.23
2016	164	687	4.19	0.24
2017	225	976	4.34	0.23
2018	237	1137	4.8	0.21
2019	233	1051	4.51	0.22
2020	266	1220	4.59	0.22
2021	335	1589	4.74	0.21
2022	377	1802	4.78	0.21
Total	**2388**	**10753**	**4.24**	**0.24**

TP = Total Publication, TA = Total Authors, AAPP = Average Author per Paper, PPA = Productivity per Author

4.10 Top Fifteen Prolific Authors

Table 10 shows the research productivity of highly prolific authors in lithium-ion batteries research during 1998-2022. The analysis included the top fifteen publications were selected during the study period.

Analysis of Record-Wise: Aravindan V is the most productive author with 49 records, followed by Mitra S with 47 records and Kumar R with 44 records. As per the table shows that remaining research data like TLCS, TGCS, cited reference, average cited reference and H-index-wise top most contributors are listed in the table.

Table 10: Top Fifteen Prolific Authors in Lithium-Ion Batteries Research

Author	**TP**	**%**	**TLCS**	**TGCS**	**CR**	**Avg.CR**
Aravindan V	49	10.27	97	1505	104	2.12
Mitra S	47	9.85	85	1444	55	1.17
Kumar R	44	9.22	29	1938	48	1.09
Ghosh S	35	7.34	28	620	27	0.77
Kalaiselvi N	33	6.92	40	793	32	0.97
Das S	32	6.71	14	466	35	1.09

Kumar A	30	6.29	18	574	21	0.7
Gopukumar S	28	5.87	72	1339	30	1.07
Reddy MV	28	5.87	93	1492	50	1.79
Bhattacharyya AJ	27	5.66	42	825	23	0.85
Kale BB	26	5.45	31	582	34	1.31
Sharma CS	26	5.45	41	527	42	1.62
Majumder SB	25	5.24	26	335	28	1.12
Kalaignan GP	24	5.03	58	521	58	2.42
Murugan R	23	4.82	60	1383	50	2.17
Total	**477**	**100**				

TP= Total Publications, %= Percentage, TLCS= Total Local Citation Score, TGLS= Total Global Citation Score, CR= Cited Reference

4.11 Top Fifteen Highly Productive Journals

Table 11 shows the total local and global citations obtained by the most productive journals selected in the top fifteen journals on lithium-ion battery research during 1998-2022.

Analysis Of Record-Wise: among the productive journals, the Electrochimica Acta with 96 records, followed by Journal of Power Sources with 85 records and IONICS with 75. As per the table shows that remaining Research data, like TLCS, TGCS, and H-Index-wise top-most contributors, are listed in the table.

Table 11: Top Fifteen Highly Productive Journals in Lithium-Ion Batteries Research

Journal	TP	Place	TLCS	TGCS	CR	Avg. CR
Electrochimica Acta	96	England	199	4208	106	1.1
Journal of Power Sources	85	Nethelands	138	4387	68	0.8
Ionics	75	Germany	85	1623	79	1.05
Journal of Energy Storage	68	Nethelands	6	2046	65	0.96
Rsc Advances	65	England	95	1950	51	0.78
Journal of The Electrochemical Society	63	Usa	49	1073	40	0.63
Journal of Alloys And Compounds	52	Switzerland	44	1119	93	1.79
Journal of Materials Chemistry A	48	England	125	3458	53	1.1
Materials Today-Proceedings	43	Nethelands	11	366	13	0.3
Journal of Materials Science-Materials In Electronics	40	Nethelands	26	492	52	1.3
Chemistryselect	39	Germany	21	415	67	1.72
Journal of Physical Chemistry C	39	USA	47	914	35	0.9
ACS Applied Materials & Interfaces	38	USA	71	2301	50	1.32
Journal of Solid State Electrochemistry	37	USA	59	709	45	1.22
Applied Surface Science	34	USA	18	773	33	0.97

TP= Total Publications, TLCS= Total Local Citation Score, TGLS= Total Global Citation Score, CR= Cited Reference

4.12 Highly Uses Document Types

Table 12 shows the preferred form of communication of the researchers in lithium-ion battery research. Articles are the most preferred form of communication among lithium-ion battery researchers out of 2388 records; 1439 (60.26%) of the documents are journal articles, which have obtained a TLCS of 1837 and TGCS of 46052. It represents the maximum number of local and global citations received by biomass energy researchers for the chosen communication method. Almost fifty per cent of the documents that the lithium-ion battery researchers used to communicate their findings are journal articles.

Table 5.12: Highly Uses Document Types in Lithium-Ion Batteries Research

Document Type	TP	%	TLCS	TGCS
Article	1439	60.26	1837	46052
Article; Early Access	404	16.92	87	4915
Proceedings Paper	212	8.88	30	644
Review	131	5.49	216	13881
Review; Early Access	118	4.94	14	3661
Article; Proceedings Paper	52	2.18	47	1495
Proceedings Paper; Early Access	20	0.84	8	178
Meeting Abstract	3	0.13	0	0
Editorial Material	2	0.08	0	41
Review; Retracted Publication	2	0.08	1	110
Article; Early Access; Retracted Publication	1	0.04	0	94
Article; Retracted Publication	1	0.04	0	146
Book Review	1	0.04	0	3
Correction	1	0.04	0	0
News Item	1	0.04	0	4
Total	**2388**	**100**		

TP= Total Publications, %= Percentage, TLCS= Total Local Citation Score, TGLS= Total Global Citation Score

4.13 Highly Cited Papers

Table 13 presents the data on the top fifteen highly cited research papers in lithium-ion batteries. The table observed that highly cited articles with the number of cited times the author of “Dutta, S; Bhaumik, A; Wu, KCW” cited from the journal “Energy & Environmental Science” by the title of “Hierarchically porous carbon derived from polymers and biomass: effect of interconnected pores on energy applications” at the year of 2014, it has cited 1154 times by the other scientists with the first rank among the selected highly cited articles. Followed by “Sathiya, M., et. al” Cited from the “nature materials” by the title of “Reversible anionic redox chemistry in high-capacity layered-oxide electrodes,” it has been cited 1110 times in 2013 by other scientists with the second rank position in the table. Next, the authors of “Balakrishnan, PG; Ramesh, R; Kumar, TP” cited from the journal of “Journal of Power Sources” by the title of “Safety mechanisms in lithium-ion batteries” which cited 914 in the year of 2006.

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Table 5.13: Highly Cited Papers in Lithium-Ion Batteries Research

Authors	TC	Source Title	Publication Year	Title
Dutta, S; Bhaumik, A; Wu, KCW	1154	Energy & Environmental Science	2014	Hierarchically porous carbon derived from polymers and biomass: effect of interconnected pores on energy applications
Sathiya, M; Rousse, G; Ramesha, K; Laisa, CP; Vezin, H; Sougrati, MT; Doublet, ML; Foix, D; Gonbeau, D; Walker, W; Prakash, AS; Ben Hassine, M; Dupont, L; Tarascon, JM	1110	Nature Materials	2013	Reversible anionic redox chemistry in high-capacity layered-oxide electrodes
Balakrishnan, PG; Ramesh, R; Kumar, TP	914	Journal of Power Sources	2006	Safety mechanisms in lithium-ion batteries
Sathiya, M; Prakash, AS; Ramesha, K; Tarascon, JM; Shukla, AK	835	Journal of The American Chemical Society	2011	V2O5-Anchored Carbon Nanotubes for Enhanced Electrochemical Energy Storage
Sathiya, M; Abakumov, AM; Foix, D; Rousse, G; Ramesha, K; Saubanére, M; Doublet, ML; Vezin, H; Laisa, CP; Prakash, AS; Gonbeau, D; VanTendeloo, G; Tarascon, JM	701	Nature Materials	2015	Origin of voltage decay in high-capacity layered oxide electrodes
Roy, P; Srivastava, SK	632	Journal of Materials Chemistry A	2015	Nanostructured anode materials for lithium ion batteries
Sarkar, A; Velasco, L; Wang, D; Wang, QS; Talasila, G; de Biasi, L; Kübel, C; Brezesinski, T; Bhattacharya, SS; Hahn, H; Breitung, B	598	Nature Communications	2018	High entropy oxides for reversible energy storage
Meshram, P; Pandey, BD;	540	Hydrometallurgy	2014	Extraction of lithium from primary

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Mankhand, TR				and secondary sources by pre-treatment, leaching and separation: A comprehensive review
Reddy, ALM; Gowda, SR; Shaijumon, MM; Ajayan, PM	447	Advanced Materials	2012	Hybrid Nanostructures for Energy Storage Applications
Punetha, VD; Rana, S; Yoo, HJ; Chaurasia, A; McLeskey, JT; Ramasamy, MS; Sahoo, NG; Cho, JW	419	Progress in Polymer Science	2017	Functionalization of carbon nanomaterials for advanced polymer nanocomposites: A comparison study between CNT and graphene
Meshram, P; Pandey, BD; Mankhand, TR	365	Chemical Engineering Journal	2015	Hydrometallurgical processing of spent lithium ion batteries (LIBs) in the presence of a reducing agent with emphasis on kinetics of leaching
Sathiya, M; Ramesha, K; Rousse, G; Foix, D; Gonbeau, D; Prakash, AS; Doublet, ML; Hemalatha, K; Tarascon, JM	335	Chemistry of Materials	2013	High Performance Li2Ru1-yMnyO3 ($0.2 \leq y \leq 0.8$) Cathode Materials for Rechargeable Lithium-Ion Batteries: Their Understanding
Rao, CNR; Gopalakrishnan, K; Maitra, U	334	ACS Applied Materials & Interfaces	2015	Comparative Study of Potential Applications of Graphene, MoS2, and Other Two-Dimensional Materials in Energy Devices, Sensors, and Related Areas
Theerthagiri, J; Salla, S; Senthil, RA; Nithyadharseni, P; Madankumar, A; Arunachalam, P; Maiyalagan, T; Kim, HS	329	Nanotechnology	2019	A review on ZnO nanostructured materials: energy, environmental and biological applications
Sivakkumar, SR; Pandolfo, AG	321	Electrochimica Acta	2012	Evaluation of lithium-ion capacitors assembled with pre-lithiated graphite anode and activated carbon cathode

TC = Total Citation

CONCLUSION

The study provides a comprehensive understanding of lithium-ion batteries research by analysing data indexed in the Web of Science database from 1998 to 2022. A total of 2,388 research publications were published, receiving 71,084 citations. In comparison, global publications in lithium-ion battery during the same period totalled 74,126 papers, which received 35,45,729 citations. A key finding of the study was the presence of fluctuations throughout the period, which are highly relevant to our understanding of this field.

There is a general progressive increase in the number of publications of lithium-ion batteries literature. However, its relative growth rate has shown a declining trend, indicating that the rate of increase is low in terms of proportion, as demonstrated by doubling time for publications, which is greater than the relative growth of total scientific publications. It indicates a decreasing trend, whereas doubling the time for publication indicates an increasing trend. The publication of data demonstrates that it was published under various headings in the relevant publications.

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