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Scientometric study of lithium ion battery research in India during 1989 to 2020

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The present paper uses scientometric indicators to examine the Li-ion battery research in India as reflected through Web of Science Core Collection (WoS) data of 32 years (1989-2020). India produced 2864 publications during the period but the publication activity increased manifold during the last decade. The output was scattered among 1346 institutions. However, 28 institutions produced 1% or more of the total output. One third (34.5%) of the output emerged out of international collaboration. About 71.5% of the output were in journals with impact factor >=2. The paper also identifies the aspects/direction of research through keyword analysis besides identifying preferred journals and prolific authors.

Keywords: Lithium-ion; Battery; Alternative Energy; Scientometrics

Introduction

During the last one decade several policy initiatives and programs were launched in India by the Ministry of New and Renewable Energy (MNRE), Government of India in the field of solar energy technologies with a primary goal to implement National Solar Mission[1]. Among the renewable sources, a lot of emphasis is being accorded to solar photovoltaics in India due to the availability of abundant sun energy for at least 300 days in a year. The success of the targeted energy initiatives employing stand alone, non-grid solar photovoltaics and other renewable energy systems can be ensured only if there is a reliable, efficient and cost effective battery backup to energise the load during the lean period. The suitable battery backup for all these requirements is based on Lithium ion (Li-ion) technology. Not only this, Li-ion batteries are also widely used in mobile phones, laptops and numerous other electronic devices.

Additionally, in the recent past the Indian Government has been wagering with the idea to gradually phase out fossil fuel based vehicles and replace them with electric vehicles (EVs). The most crucial part of an EV is the battery. Most of these advanced EVs are using the Li-ion battery in place of conventional fuel used in the combustion engine[2]. It is estimated that by 2050, EVs will have a share of about 60% of the total personal vehicles[3,4] around the globe. Thus, Li-ion battery has come into centre stage for critical success in several technology spheres "due to its high energy density, low self-discharge property, long life span, high open-circuit voltage and nearly zero memory effects"[5]. According to NITI Aayog, the shift to 100% EVs can create $ 300 billion domestic battery market.

On 23rd September, 2019 the Prime Minister of India while speaking at Climate Action Summit 2019 during the 74th session of the United Nations General Assembly remarked about making India's transport sector green through e-mobility (https://www.pmindia.gov.in). A report by Indian Governments' think tank NITI Aayog and Rock Mountain Institute 2017 highlights India's potential for leading the world in the deployment of electric mobility system which can create large and lasting national benefits[6]. Batteries account for one third of the total purchase price of the EVs and continuous innovations in battery technology accompanied with increased production scale are driving a steep decline in prices. Nearly 80% drop in Li-ion battery pack prices over the past 5 years has made high mileage electric service vehicles cost competitive in terms of the cost of the ownership[7].

According to Bloomberg New Energy Finance Data, the demand for Li-ion batteries in the 2020 was estimated at about 123 gigawatts (GW) and projected its rise to 1293 GW by 2030[8]. In March 2016, the Government of India set the country's sights on an ambitious target of 100% EVs by 2030[9]. India's per capita car ownership is quite low with fewer than 20 vehicles per thousand citizens (compared to 800 per 1000 in the US and 85 per thousand in China). However, India's personal car ownership is rising by 10% annually for the past decade with more than 60000 new vehicles registered per day and it is estimated that an average Indian will travel 6000 km/year by 2050[10]. The successes of all these ambitious targets reinforce the critical importance of energy efficient, reliable and economical Li-ion batteries.

Li-ion battery is a type of rechargeable battery, first proposed by chemist M Stanley Whittingham in the 1970s[11]. He is considered as the founding father of rechargeable Li-ion battery and was one of the recipients of 2019 Nobel Prize in chemistry for his pioneering development work on Li-ion battery. However, use of commercial Li-ion batteries was started in 1991, in portable devices like mobile phones, digital cameras, handheld game machines and laptops[12]. The Li-on batteries are considered better than others as its energy density is almost twice that of the standard nickel-cadmium batteries. It has demonstrated a much longer lifetime, lasting at least 10+ years and 7000+ charge/discharge cycles and is low maintenance battery among different type of batteries[12]. Experts agree that these batteries are safer in commercially available vehicles in case of a collision than gasoline-propelled cars with a gasoline tank[13].

In late 1990's, Li-ion batteries were found to be most suitable for the hybrid EVs[14] which gradually changed entire personal transport scenario radically[15,16]. Ever rising prices of petroleum will create much more demand for EVs and this may lead to mass production of batteries which will further lower the prices of Li-on batteries[17,18,19]. However, questions are raised about the smooth supply availability of lithium and cobalt in India as we do not have these metal reserves in our country. Cobalt is also one of the essential ingredients used to prevent battery overheating in the Li-ion battery. The lithium triangle comprising of Chile, Bolivia and Argentina are endowed with 75% high quality existing known reserves[20].

For ensuring uninterrupted supply of the metal India has signed a Memorandum of Understanding with Bolivia to facilitate Bolivian supplies of lithium carbonate to India and promote lithium battery/cell production plants in India which provide it with access to the lithium reserve of the country[21]. A strategic partnership by India with a member country from lithium triangle suggests India's intent to surmount the constraints of lithium supplies to ensure its long term plans succeed without any hurdle. At the same time indigenous efforts for exploration of lithium resources continue in the country. Recently preliminary surveys by the Atomic Minerals Directorate for Exploration and Research an arm of the Department of Atomic Energy of the Government of India are learnt to have shown the presence of 1600 tonnes of Lithium resources in Mandya district of Karnataka[22].

The importance of this transformative technology which has already touched the lives of billions of people around the world can be well comprehended by the fact that 2019 Chemistry Nobel Prize was bagged by three scientists whose research work focussed on different aspects of Li-ion battery. In this background, it becomes pertinent to examine indigenous research and development dynamics in the field of Li-ion battery research in India. A study published in 2011 entitled "Bibliometric analysis of global Li-ion battery research trends from 1993 to 2008"[23], indicated that China, USA and Japan were the most productive countries and India ranked 7th in the field of Li-ion battery research.

CSIR-Central Electrochemical Research Institute (CECRI), Karaikudi in Tamil Nadu, a national laboratory under the Council of Scientific and Industrial Research (CSIR) has developed India's first indigenous Li-ion battery[24] in 2016. It has started fabrication of 400mAh battery. The battery of this capacity has very limited applications in solar power lantern, heating power tools, firing torpedoes, lighting and signalling of railways etc. Recently CSIR-CECRI also transferred know how on Li-ion battery technology to M/S Tata Chemicals Limited, Mumbai. Many CSIR laboratories are pooling their efforts and potential in the area as a result of which they have developed 3.6 V, 650 mAH 18650 Li-ion cells using electrodes from CSIR-National Physical Laboratory (NPL), New Delhi and separators from CSIR-Central Glass & Ceramic Research Institute (CGCRI) Kolkata. CSIR-CECRI patented Lithium Ion Battery (LIB) electrode materials and the fabrication facilities to make 2AH pouch and 18650 Li-Ion batteries.

Vikram Sarabhai Space Centre (VSSC), Trivandrum has a larger facility to produce space quality Li-Ion batteries in the range of 1.5-100 AH. Several IITs and Indian Institute of Science (IISc), Bangalore are involved in R&D work pertaining to Li-ion batteries[25]. Among others, research focus and agenda on Li-ion batteries include safety and temperature tolerance, cost effectiveness, charging/discharging cycling and speed, life extension, energy density and recycling, etc.,[26,27].

The present paper attempts to make an assessment of research and development in India in the field of Li-ion battery research using bibliometric/ scientometric indicators based on research publications indexed in WoS.

Objectives of the study

- To identify the prolific institutions involved in research and to study their impact;
- To study aspects of co-authorship and pattern of collaboration using scientometric indicators;
- To gain an insight into direction/aspects of research through keyword analysis;
- To identify most preferred journals, their country of origin and Impact Factor (IF); and
- To identify most productive authors in Li-ion battery research.

Methodology

Data was downloaded from Web of Science Core Collection up to the year 2020 on 15 January 2021. Data was downloaded using search criteria used in an earlier study[28] giving terms in the topic field. The search criteria included keywords "Li-ion", Li-ions", "Li ion" "Li ions", Lithium-ion", "Lithium-ions", Lithium ion", "Lithium ions", "cathode", "cathodes", "anode", "anodes", "electrolyte", "electrolytes,", "electrode", "negative electrode", "negative electrodes", "positive electrode", "positive electrodes", "battery", "batteries", "cell", "cells" . The search yielded 2909 records including 2403 article, 318 proceeding papers, 143 reviews and 45 other documents including early access article (28), early access reviews (7), meeting abstracts (6), editorials (2), and correction and news item one each. However, only articles, proceedings papers and reviews constituted the data for our study.

Before undertaking data analysis, standardisation of the data was carried out. Variations in the name of the same institution were standardized to make the data amenable to authentic analysis. Field stations or research centres of the institutions were assigned the name of the parent institution. Thereafter, the data was enriched by adding IF of the journals using JCR for the year 2019. Countries of all the collaborating author(s) and country of the origin of journals were also required to be identified and entered into the database. The number of author(s) was counted and entered into the database as well.

Thereafter, bibliometric / scientometric indicators were applied to understand the gamut of research and development in the field of Li-ion battery research in India.

Results

During the course of 32 years from 1989 to 2020 India produced 2864 research publications spread over 592 sources (including journals and proceedings) originating from 23 countries. Research output in Li-ion battery research in India started in the year 1989, however, in the years 1990, 1991 and 1994 there was no publication. During the first 10 years, that is, upto the year 1998 only 13 papers were published.

The Li-ion battery research in India seems to have taken off around the year 2001 and gradually growing with successive inflection points from the years 2005-08 onwards marked with a rising trajectory (Fig. 1).

To gain further insight into the rising trend of the research output we have grouped the entire output of 32 years in 6 blocks. The first block constitutes 7 years while the remaining are of 5 years each (Table 1). The initial block comprising 7 years accounted for 4 publications only as in the years 1990, 1991 and 1994 there was no publication. The last decade accounts for 89% of the output. The output remained within two digits up to the block years 2001-2005. In the subsequent blocks the output almost triples every 5 years.

The substantial rise in the research output during the last decade (2011-15 and 2016-20) may be attributable to direct or indirect impact of the major push exercised in accordance with various policy measures and schemes launched by the Government of India to meet electricity requirements using clean and renewable energy sources (http://mnre.gov.in) of intermittent nature requiring the use of storage batteries and additionally, for a plethora of electronic gadgets and devices including mobile phones[29].

Citations and impact of the output

Citation counts indicate the impact and visibility of an author or a group of authors on the universe of the

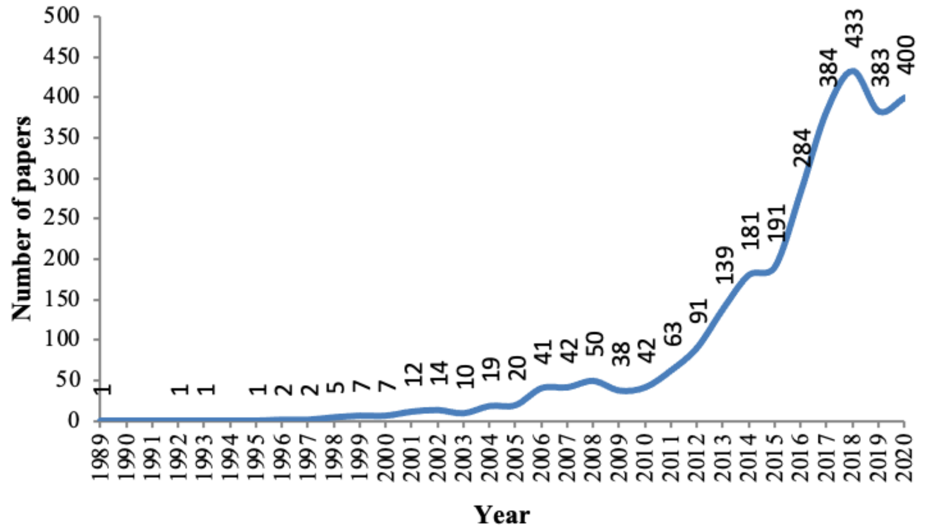

Fig. 1—Publication in Lithium-ion battery research during 1989-2020

Table 1—Research output in blocks of years

Blocks Number	Block years	No. of papers	Percent of papers
1	1989-1995	4	0.1
2	1996-2000	23	0.8
3	2001-2005	75	2.6
4	2006-2010	213	7.4
5	2011-2015	665	23.2
6	2016-2020	1884	65.8
Total	1989-2020	2864	100.0

Table 2—Citation distribution Vs number of publications

No. of citations	No. of papers	Percent of papers	Cumulative % of papers	No. of citations
0	398	13.9	13.9	0
1	268	9.4	23.3	268
2	187	6.5	29.8	374
3	167	5.8	35.6	501
4	149	5.2	40.8	596
5	126	4.4	45.2	630
6-10	445	15.5	60.7	3479
11-20	472	16.5	77.2	6980
21-30	219	7.7	79.9	5428
31-40	114	4.0	83.9	4032
41-50	86	3.0	87.9	3860
51-100	165	5.8	93.7	11317
>100	68	2.4	100.0	14017
Total	2864	100.00		51482

research community. Citation analysis is considered as an important tool to make scientometric assessment. In all 2864 papers received 51482 citations, resulting in 17.98, say 18 Citations Per Paper (CPP). Table 2 indicates that about 9.4% papers received one citation each whereas 13.9 % papers did not get any citation. About 31% of the papers received 1-5 citations and almost the same proportion of publications received 6-20 citations.

Table 3—Distribution of output according to the Impact Factor (IF) of the journals

Impact Factor	Number of Papers	Percent of Papers	Cumulative % of Papers
0 - <=1	484	16.9	16.9
1-<= 2	332	11.6	28.5
2- <=3	673	23.5	52.0
3 - <=4	494	17.3	69.3
4 - <=5	369	12.9	82.2
5 - <=10	442	15.4	97.6
>10	70	2.4	100.0
Total	2864	100.00	

Sixty eight papers (2.4%) received more than 100 citations each accounting for a total of 14017 citations.

Table 3 suggests that the papers published in journals bearing IF range from 0-1 accounted for 16.9% of the output. More than half of the research output was published in journals with IF in the range of 2-5. More than 2% papers emerged in the journals bearing IF greater than 10. This suggests that more than two thirds of the research output was published in the journals bearing respectable IF.

Prolific institutions

The entire output was scattered over 1344 institutions, however, 27 institutions produced 1% or more of the total publications which are listed in Table 4 These 27 institutions received about 70% of the citations and their CPP was 21.6 whereas its overall value was 18. The highest CPP (44.4) was

Table 4—Prolific institutions and their citations

Sl. no.	Institute	NP	PNP	TC	PTC	RCI	CPP
1	CSIR-Cent. Electrochemical Res. Inst. Karaikudi	295	10.30	9349	18.16	1.8	31.7
2	Indian Institute of Science, Bangalore	203	7.09	5831	11.33	1.6	28.7
3	Alagappa University, Karaikudi	139	4.85	3171	6.16	1.3	22.8
4	Indian Institute of Technology, Bombay	117	4.09	2739	5.32	1.3	23.4
5	Indian Institute of Technology, Madras	105	3.67	1639	3.18	0.9	15.6
6	Indian Institute of Technology, Kharagpur	96	3.35	1673	3.25	1.0	17.4
7	Pondicherry University, Pondicherry	78	2.72	1492	2.90	1.1	19.1
8	Bharathiar University, Coimbatore	74	2.58	1040	2.02	0.8	14.1
9	Indian Inst of Technology, Roorkee	57	1.99	402	0.78	0.4	7.1
10	Indian Inst of Technology, Hyderabad	56	1.96	1008	1.96	1.0	18.0
11	CSIR-National Chemical Lab., Pune	54	1.89	1574	3.06	1.6	29.1
12	CSIR-Cent. Glass & Ceramic Res Inst., Kolkata	49	1.71	1516	2.94	1.7	30.9
13	Indian Inst. of Technology, Kanpur	46	1.61	676	1.31	0.8	14.7
14	Vellore Institute of Technology, Vellore	45	1.57	648	1.26	0.8	14.4
15	SRM Institute of Science and Technology, Chengalpattu	41	1.43	308	0.60	0.4	7.5
16	International Advanced Research Centre for Powder Metallurgy and New Materials, Gurugram	41	1.43	799	1.55	1.1	19.5
17	Bhabha Atomic Research Centre, Mumbai	40	1.40	504	0.98	0.7	12.6
18	CSIR-National Physical Lab., Delhi	38	1.33	1226	2.38	1.8	32.3
19	University of Delhi, Delhi	36	1.26	656	1.27	1.0	18.2
20	Indian Institute of Science Education and Research, Tirupati	35	1.22	366	0.71	0.6	10.5
21	Amrita Vishwa Vidyapeetham	32	1.12	83	0.16	0.1	2.6
22	Indian Assoc. for Cultivation of Sci. Kolkata	31	1.08	1377	2.67	2.5	44.4
23	Banaras Hindu University	30	1.05	918	1.78	1.7	30.6
24	Indian Institute Of Technology, Delhi	30	1.05	193	0.37	0.4	6.4
25	Jawaharlal Nehru Ctr. for Advanced Scientific Research, Bangalore	29	1.01	1079	2.10	2.1	37.2
26	Indian Institute of Science Education and Research, Pune	29	1.01	478	0.93	0.9	16.5
27	Savitribai Phule University, Pune	28	0.98	227	0.44	0.4	8.1
	Sub-total	1665	58.14	35953	69.84	1.2	21.6
	Others (1318 institutes)	1199	41.86	15529	30.16	0.7	13.0
	Total	2864	100.0	51482	100.0	1.0	18.0

NP=Number of Papers; PNP=% of Papers; TC=Number of Citations; PTC=% of Citations

observed in case of Indian Association for the Cultivation of Science (IACS), Kolkata followed by (37.2) in respect of Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bangalore. Out of the 27 prolific institutions, four belong to CSIR family, namely CSIR-CECRI; Karaikudi, CSIR-CGCRI; Kolkata, CSIR-NCL; Pune and CSIR-NPL; New Delhi.

Out of these four CSIR institutions, CSIR-CECRI outperformed all the 27 institutions in terms of quantum of research publications. It was followed by Indian Institute of Science (IISc), Bangalore, Alagappa University, Karaikudi (AU), Indian Institute of Technology, Bombay (IITB), Indian Institute of Technology, Madras (IITM) and Indian Institute of Technology, Kharagpur (IITKH). These six institutions accounted for about one third of the total publications. The RCI of these 27 institutions combined was greater than 1 reflecting above average performance of the prolific institutions. RCI is the ratio of % of citations to % of papers. RCI=1 indicates that institutions are performing at average for that field of research. RCI>1 indicates that the institutions are performing better than others and RCI<1 indicates the institutions are performing below average for that area of research.

Seven universities figured among these 27 institutions and out of these only three universities, namely, Alagappa University, Pondicherry University, and Banaras Hindu University had RCI>1 whereas Amrita Vishwa Vidyapeetham and Savitribai Phule University had low RCI value. Among the prolific institutions, the lowest RCI was obtained in respect of SRM Institute of Science & Technology; Chengalpattu, Indian Institute of Technology; Roorkee (IITR) and Indian Institute of Technology; Delhi. However, in all ten institutions had RCI<1 which included institutions like Bhabha Atomic Research Centre (BARC) and some IITs.

Table 5—Most prolific authors

Sl. no.	Name and affiliation of most prolific authors	No. of papers	Mean citations
1	Aravindan, Vanchiappan, Indian Institute of Science Education & Research, Tirupati	66	23.7
2	Mitra, Sagar, Indian Institute of Technology, Bombay	62	23.7
3	Munichandraiah, Nookala, Indian Institute of Science, Bangalore	46	28.5
4	Kalaiselvi, Nallathamby CSIR- Central Electrochemical Research Institute, Karaikudi	44	18.3
5	Gopukumar, Sukumaran, CSIR- Central Electrochemical Research Institute, Karaikudi	38	32.3
6	Selvasekarapandian, Subramaniam, Materials Research Center, Coimbatore	35	19.2
7	Bhattacharyya, Aninda Jib, Indian Institute of Science, Bangalore	34	24.4
8	Mahanty, Sourindra, CSIR-Central Glass & Ceramic Research Institute, Kolkata	34	35.7
9	Rajendran, S., Alagappa University, Karaikudi	34	39.9
10	Ogale, Satishchandra, Indian Institute of Science Education & Research, Pune	34	33.9
11	Nair, Shantikumar V., Amrita Vishwa Vidyapeetham, Coimbatore	33	8.6
12	Varadaraju, U. V.,Indian Institute of Technology, Madras	30	17.0
13	Barpanda, Prabeer, Indian Institute of Science, Bangalore	30	32.6
14	Ramesha, Kannadka, CSIR- Central Electrochemical Research Institute, Karaikudi	29	97.0
15	Kalaignan, G. Paruthimal, Alagappa University, Karaikudi	28	19.4
	Sub-total	577	30.3
	Total number of authors = 6066	2864	18.0

All the CSIR institution had RCI>1 which suggests that not only the CSIR institutions figure among the top performing institutions in terms of quantum of output but their citations were high too. Among these four CSIR institutions, CSIR-CECRI and CSIR-NPL had RCI=1.8 which was quite high.

IIT Roorkee and IIT Delhi were characterised with the least RCI among seven IITs whereas IITB had RCI>1 and IITKH had RCI=1. The highest RCI (2.5) was observed in respect of IACS, Kolkata followed by JNCASR, Bangalore (2.1).

Fifty five percent of the research output was from academic institutions followed by IITs/Engineering Colleges (49%), research institutions (30%) and private Indian and foreign industrial entities (15%). In the prolific institutions as well almost similar pattern emerges except for the absence of private industrial units. It must be pointed out here that the total of the percentages exceeds 100% because of the involvement of collaboration by different sectors in the research output.

It is also noteworthy that one of the papers published from CSIR-CECRI in the year 2006 in *Journal of Power Sources* on the aspect of safety mechanisms in Li-ion batteries received the 3rd highest citation 688 among all 2864 publications. This paper entitled "safety mechanisms in Lithium-ion batteries" was an independent and indigenous outcome of CSIR-CECRI without any involvement of domestic or international collaboration.

Most prolific authors

Some authors have performed exceedingly well and are reflected in Table 5 listing 15 authors who have published 1% or more papers along with their respective affiliation.

Out of these 15 authors, three belong to CSIR-CECRI, Karaikudi and one to CSIR-CGCRI, Kolkata. Out of the four prolific authors from CSIR in the list, three had CPP much above the overall CPP and one had even more than five times that of CPP. The top author in the list was Vanchiappan Aravindan, from Indian Institute of Science Education & Research, Tirupati followed by Sagar Mitra from IITB.

Three authors in the list belonged to IISc and another two to Alagappa University. Mean citation for Li-ion battery research papers published by these prolific Indian researchers was 30.3 whereas the CPP for the entire output was 18. More than half of the Indian prolific authors working in the field of Li-ion battery research had relatively higher CPP as compared with overall CPP. It indicates that their work is decidedly relevant to the field of Li-ion battery research and they are well connected with the researchers around the world engaged in the pursuit of Li-ion battery research.

Publications by some authors were highly cited but they were isolated cases as except for one, namely, Ramesh Kannadka of CSIR-CECRI who had 29 publications none other figured in the list of prolific authors. The number of such authors was 249 who produced 496 (17%) papers bearing three times the value of CPP. However, two more authors out of 249 had publications in double digit and the rest had in single digit. Most of these may be construed as outliers as 157 authors had one paper each, 55 had two papers each and 9 had three papers each. The highest citation

(819) was received by Saikat Datta who had one paper followed by 688 citations received by P.G. Balakrishnan. This seems to suggest that most of the highly cited authors may not be prolific authors as well.

Co-authorship and pattern of collaboration

Gone are the days when science used to be the pursuit of individual scientists. Since the last century scientific research is increasingly becoming a collective endeavour. At micro level scientists within an institution / organisation may come together to work on a common problem to produce new scientific knowledge and it may be scaled up to collaboration among scientists of two or more different institutions within or outside the country. Modern scientific research is becoming increasingly complex. It requires participation of skills, from diverse fields as well as resources to solve the problems. Therefore, co-authorship and collaboration become an important integral aspect of scientific pursuit in the modern times.

Co-authored publications can be used as a basic counting unit for measuring collaborative activity[30,31]. Table 6 shows that out of 2864 publications only 45 (1.6%) were single authored papers. Only 68 (2.4%) papers were authored by ten or more researchers. The highest proportion of papers (22.7%) had 3 authors.

To demonstrate the pattern of co-authorships in a discipline, a number of bibliometric indicators have been suggested. The mean number of authors per paper, termed as the Citation Index (CI) by Lawani[32], proportion of multiple-authored papers, called Degree of Collaboration (DC) by Subramanyam[33] as a measure of the strength of collaboration in a discipline are two such indicators. Ajiferuke[34] also presented another collaboration measure called Collaboration Coefficient (CC) which incorporates the merits of both of the CI and DC. CC lies between 0 and 1, with 0 corresponding to all single-authored papers. However, it is not 1 for the case where all papers are maximally authored, i.e. every publication in the collection has all authors in the collection as co-authors. These three measures can be given as:

Table 6—Distribution of number of authors and publications

No. of authors	No. of papers	% age of papers	CPP
1	45	1.6	13.7
2	527	18.4	16.1
3	649	22.7	17.2
4	550	19.2	15.1
5	416	14.5	21.6
6	274	9.7	19.6
7	165	5.8	16.6
8	112	3.9	19.1
9	58	2.0	19.9
10 or more	68	2.4	37.7
Total	2864	100.0	18.0

Collaboration Coefficient (CC)= 0.71
Degree of Collaboration (DC) =0.99
Collaboration Index (CI) =4.27

Let the collection K be the research papers published in a discipline or in a journal during a certain period of interest.

fj = the number of papers having j authors in collection K;
N = the total number of papers in K; N = Pj fj; and
A = the total number of authors in collection K.

Collaborative Index (CI)

One of the early measures of degree of collaboration is CI is given by:

$$\mathrm{Cl} = \left(\sum_{j=1}^{k} jfj\right)/N$$

It is a measure of mean number of authors per paper. Although it is easily computable, it is not easily interpretable as a degree, for it has no upper limit. Moreover, it gives a non-zero weight to single-authored papers, which involve no collaboration. CI is average number of authors per paper is calculated.

Degree of Collaboration (DC)

Degree of Collaboration (DC) is given by:

$$\mathrm{DC} = 1 - \frac{f1}{N}$$

DC is easy to calculate and easily interpretable as a degree (for it lies between zero and one), gives zero weight to single-authored papers, and always ranks higher a discipline (or period) with a higher percentage of multiple-authored papers. However, DC does not differentiate among levels of multiple authorships. DC essentially indicates fraction of multi-authored papers.

Collaboration Coefficient (CC)

Collaboration Coefficient (CC) is given by:

$$CC = \left(\sum_{j=1}^{A} (1/\,\mathrm{j})\, fj\right)/\,\mathrm{N}$$

It vanishes for a collection of single-authored papers, and distinguishes between single authored, two-authored, three-authored papers, etc. However, CC fails to yield 1 for maximal collaboration, except when number of authors is infinite. CC is indicated as zero for a data set containing all the single author papers and ‘one’ for infinite number of co-authored papers. It is considered as more compact indicator of authorship

Table 7—Distribution of research output according to nature of collaboration

Block Years	Type of Collaboration						Group Total	
	Domestic		International		None			
	Papers	%	Papers	%	Papers	%	Papers	%
1989-1995	4	0.2					4	0.14
1996-2000	17	0.9	6	0.6			23	0.80
2001-2005	57	3.1	18	1.8			75	2.62
2006-2010	138	7.5	70	7.1	5	12.5	213	7.44
2011-2015	419	22.8	235	23.8	11	27.5	665	23.22
2016-2020	1201	65.4	659	66.7	24	60	1884	65.78
Total	1836	100.0	988	100.0	40	100	2864	100.00
Citations per Paper	14.92		23.95		10.18		17.98	

pattern than CI and DC, as it takes all single authored and multi-authored papers into consideration.

Table 7 suggests that out of the total 2864 publications, 1836 (64.1%) of the papers involved domestic collaboration, 988 (34.5%) emerged out of international collaboration and 40 (1.4%) with no collaboration (NC). With the passage of time the quantum of collaborative effort, both domestic as well as international gradually increased. It also indicates that papers emerging out of international collaboration had an average CPP of 23.95 whereas its value was only 14.92 in case of domestic collaboration in case of Li-ion battery research in India.

In all Indian researchers have collaborated with their counterparts from 59 different countries. Table 8 lists top 20 collaborating countries with which Indian researchers engaged in pursuit of research. The major collaborating country is South Korea (282), followed by USA (144), Singapore, Japan, China, Australia, Taiwan and France.

A small percent of industries including, both Indian and foreign, too played a part in contributing and accounted for 434 publications. In all there were 56 units: Indian (31), US (8), Singapore (6), Spain (3) and others belonged to Australia, Japan, South Korea, Switzerland, UK and China. However, all indigenous units had collaborated either with academic institutions or research institutions in India or abroad. The industrial entities that made significant number of publications included Samsung India and their counterpart in South Korea, (40), Amar Raja Batteries India (15), General Motors India and their principal in USA (17).

At the same time IF value of internationally collaborated publications was 4.42 as compared with IF value of 3.2 for overall publications. The highest CPP (58.3) of the internationally collaborative output was obtained in respect of France followed by Japan (34.3), Brazil (32.2), Singapore (31.5) and USA (30.7). However, collaboration with some other countries did not yield even the value of overall CPP of 18. The countries reflected above were among the top performing entities in the field of Li-ion battery research as well as top exporter of Li-ion batteries in the world[35].

Table 8—Research output with dominant collaborative countries

Sl. no.	Collaborating countries	NP	CPP
1	South Korea	282	19.5
2	USA	144	30.7
3	Singapore	109	31.5
4	Japan	79	34.3
5	China	77	9.4
6	Australia	67	23.5
7	Taiwan	61	27.2
8	France	54	58.3
9	United Kingdom	44	11.9
10	Germany	42	27.4
11	Malaysia	27	11.0
12	Canada	27	15.0
13	Saudi Arabia	22	20.1
14	Spain	22	14.6
15	Sweden	20	18.4
16	Russia	19	10.5
17	Norway	18	10.4
18	Israel	15	21.4
19	Italy	12	21.2
20	Brazil	10	32.2
	Sub-total	943	24.58
	Others (39 countries)	45	10.89
	Total	988	23.95

*NP- No. of papers; PNP-Proportion of papers; CPP=Citation per paper

Direction/aspects of research

The direction/aspects of research are examined through analysis of the keywords which are given by the authors in the publications and descriptors assigned by the publishers of the database. The research output of 2864 publications contained 30848 author keywords including descriptors assigned by the publishers. These keywords were highly scattered into 8334 different entities which were reduced to 4531 standardized keywords. Here standardization means clubbing the different variants of the same keyword to make the analysis more cogent and meaningful. For example, "x-ray diffraction", x ray diffraction", "xray diffraction", and "XRD" were all considered as one keyword. These standardized author keywords were computed and ranked in 5 year time periods from the year 2006. However, prior to that the entire period was considered as a single block as only 102 publications appeared in the initial 17 years period. The last block in the table reflects the total aggregation over the entire period from 1989-2020 along with the number of publication in which these different keywords appeared. Table 9 gives the list of top 20 standardized author keywords.

The distributed ranking of keywords over block periods of time shows the dynamics of research emphasis. The rankings varied during different time periods thereby implying that emphasis on certain aspects kept changing over the period of study. We notice that supercapacitor, graphene and EV figure only during the last decade. This suggests that a decade ago these aspects were not being focussed upon by the researchers. The top ranked five keywords are "li-ion batteries", "anode", "cathode", "x-ray diffraction" and "ionic conductivity". The rank of certain keywords like "energy storage", "dielectric", "charge-discharge" and "sol-gel", over the period of study have moved up from lower ranks to higher ranks, signifying the substantial increasing focus and emphasis these aspects are being accorded.

Similarly "electrochemical performance" and "electric vehicle" moved up drastically from rank 125 and 126 respectively. The upward arrows in the table indicate a general tendency of upward movement of ranking of these keywords. X-ray diffraction, cyclic voltametry, FTIR (Fourier Transmission Infrared) and impedance spectroscopy are the main test methods used in the Li-ion battery research. There is no significant variation in the ranks of "x-ray diffraction" and "cyclic voltammetry" whereas the rank of FTIR moves up but that of impedance spectroscopy moves down which implies that these test methods continue to be used though with some variations over the period. However, through the keyword analysis we have not found any evidence of recycling of lithium material which is very crucial due to the limited lithium resources in India and high dependence on import from countries rich in lithium resources.

Country of origin of journals

Overall 2864 papers were published in journals originating from 23 countries. Table 10 indicates that about 97% of the papers were published in the journals originating from the scientifically advanced countries like USA, UK, the Netherlands, Germany and Switzerland indicating that the Indian scientific output in Li-ion battery research was at par with the mainstream international science in the field. However, only 70 papers which accounted for about 2.4% of the total output originated from 17 Indian journals. However, out of these Indian journals, five, namely, *Bulletin of Materials Science (24), Transactions of the Indian Institute of Metals (7), Journal of chemical sciences (6), Current Science (5), Asian Journal of Chemistry (4)*

Table 9—Top 20 author keywords

Top 20 Keywords	1989-2005		2006-2010		2011-2015		2016-2020		1989-2020		
	Rank	%	Rank	%	Rank	%	Rank	%	Rank	Np	%
Li Ion Battery	1	8.4	1	15.8	1	15.5	1	15.1	1	794	17.5
Anode ↑	15	1.3	6	2.7	3	4.4	2	4.8	2	230	5.1
Cathode ↑	15	1.3	2	5.3	5	2.7	4	2.1	3	131	2.9
X-Ray Diffraction	4	3.1	3	4.9	2	4.6	7	1.4	4	130	2.9
Ionic Conductivity	5	2.7	4	3.1	4	3.7	5	1.8	5	124	2.7
Supercapacitor ↑	0	0.0	0	0.0	12	1.4	3	2.2	6	90	2.0
Cyclic Voltammetry	11	1.8	7	2.5	10	1.7	8	1.2	7	77	1.7
Energy Storage ↑	225	0.4	50	0.6	13	1.2	6	1.4	8	67	1.5
Electrochemical Properties	45	0.9	5	2.9	6	2.4	22	0.7	9	66	1.5
Polymer Electrolyte	3	3.6	17	1.0	11	1.6	16	0.8	10	57	1.3
Batteries	0	0.0	14	1.2	15	1.1	9	1.1	11	55	1.2
Dielectric ↑	225	0.4	125	0.4	8	1.8	12	0.9	12	54	1.2
Charge-Discharge ↑	(15)	(1.3)	8	1.8	7	2.0	32	0.6	13	52	1.2
FTIR ↑	3	3.6	50	0.6	24	0.8	15	0.8	14	47	1.0
Graphene	0	0.0	0	0.0	10	1.7	19	0.7	15	43	1.05
Sol-Gel ↑	(15)	(1.3)	10	1.6	27	0.7	17	0.7	16	42	0.9
Electrochemical Performance ↑	0	0.0	125	0.4	37	0.6	12	0.9	17	40	0.9
Electric Vehicle ↑	0	0.0	0	0.0	126	0.3	10	1.0	18	38	0.8
Conductivity	11	1.8	50	0.6	37	0.6	22	0.7	19	37	0.8
Impedance Spectroscopy ↓	(4)	(1.8)	12	1.4	37	0.6	27	0.6	20	36	0.8

↑ - indicates rank of keyword indicating a tendency to move upwards over the period of time account for 65% of the papers on Li-ion battery research published in Indian journals.

Most preferred journals and their impact

About 17% papers were published in journals with IF <= 1. More than 70% of the research output was published in journals having IF > 2. Merely 70 (2.4%) papers were published in journals with IF>10.

In all, 70 papers were published in journals that had IF>10 out of which eleven papers were published in journals having IF>25. Notable among them were two papers published in the journal *Nature Materials* which had the highest IF value of 38.891, three papers in the journal *Progress in Materials Science* (IF=31.08), one paper in the journal *Progress in Polymer Science* (IF=27.18), and five papers in *Energy & Environmental Science* (IF=25.42).

Table 11 lists most preferred journals along with their IF. The entire output was scattered in 592 sources (including journals and proceedings). However, only 27 journals which published more than 25 papers which accounted for about 48% of the total output are listed here. All these journals have

Table 10—Distribution of the output according to the journal publishing country

Sl. no.	Journal publishing country	Number of papers	Percent of papers	Number of journals	Percent of journals
1	USA	905	31.6	272	46.0
2	England	770	26.9	107	18.1
3	Netherlands	541	18.9	68	11.5
4	Germany	304	10.6	46	7.8
5	Switzerland	190	6.6	38	6.4
6	India	70	2.4	17	2.9
	Sub-total	2780	97	548	92.7
	Others* (17 countries)	84	2.9	44	7.4
	Total	2864	100.0	592	100.0

Others* – Singapore, South Korea, France, Canada, Serbia, China, Poland, Brazil, Austria, Norway, Greece, Japan, Romania, Russia, Slovenia, Vietnam and Turkey

Table 11—Most preferred journals

Sl. no.	Most productive Journals	Country	No. of Papers	Impact Factor
1	*Electrochimica Acta*	England	140	4.803
2	*Journal of Power Sources*	Netherlands	126	6.333
3	*Ionics*	Germany	116	2.119
4	*RSC Advances*	England	94	3.289
5	*Journal of the Electrochemical Society*	USA	77	3.014
6	*Journal of Materials Chemistry-A*	England	66	8.262
7	*Journal of Solid State Electrochemistry*	USA	58	2.327
8	*Journal of Physical Chemistry-C*	USA	53	4.509
9	*Journal of Alloys and Compounds*	Switzerland	52	3.014
10	*Solid State Ionics*	Netherlands	50	2.380
11	*Chemistryselect*	Germany	48	1.460
12	*Journal of Materials Science-Materials in Electronics*	Netherlands	42	1.798
13	*ACS Applied Materials & Interfaces*	USA	41	7.145
14	*Applied Surface Science*	Netherlands	40	3.150
15	*Materials Letters*	Netherlands	31	2.437
16	*Ceramics International*	England	31	2.758
17	*Journal of Nanoscience and Nanotechnology*	USA	31	1.338
18	*Materials Today-Proceedings*	Netherlands	31	0.000
19	*Materials Research Bulletin*	England	30	2.435
20	*New Journal of Chemistry*	England	29	3.227
21	*Physical Chemistry Chemical Physics*	England	29	4.449
22	*Materials Chemistry and Physics*	Switzerland	29	2.101
23	*ACS Applied Energy Materials*	USA	27	4.473
24	*Materials Research Express*	England	26	0.968
25	*Journal of Energy Storage*	Netherlands	26	3.940
26	*Journal of Electroanalytical Chemistry*	Switzerland	26	2.822
27	*Carbon*	England	25	6.198
	Sub-total		1374	
	Others (592 – 27 = 565)		1490	
	Total (592 Journals)		2864	

respectable IF. Three journals namely *Journal of Material Chemistry-A (8.262)*, *ACS Applied Materials & Interfaces (7.145)* and *Journal of Power Sources (6.333)* are indicated with significantly higher IF.

Conclusion

The emphasis by the Government of India to put policy framework for research agenda in order to develop Li-ion batteries as a power back up for renewable power sources including solar devices and as a source to drive EVs seems to have reflected in growth of publications during the recent past. The study revealed that the number of research papers increased from mere one paper in 1989 to 383 papers in year 2019 and 400 in 2020. From the year 2013 the output remains in three digit and shows a rising trend. The CPP value of the entire output was about 18. Among the prolific institutions included four CSIR institutions, six IITs, IISc, two DST institutions, DU, IISER and BARC. CSIR-CECRI not only outperformed all other institutions but its RCI too was quite high among the prolific institutions. The analysis of highly productive authors shows that authors from different CSIR laboratories, IITs and IISc were actively involved in the field of Li-ion battery research; they also gained higher number of citation than the average citation of research papers from India.

Indian researchers engaged in Li-ion battery research have collaborated with authors from 59 other countries**.** However, the foremost collaboration was forged with their counterparts from South Korea followed by the United States, Singapore, Japan and China. On the one hand, internationally collaborated papers with some countries have yielded higher value of CPP, on the other hand collaboration with some other countries did not even attain the overall value of CPP. This suggests that international collaboration may not necessarily result in high quality papers. A raw analysis in the Web of Science indicates that China is the leading country in the world in the field of Li-ion battery research, however, Indian authors had only 12 out of 988 internationally collaborative research papers with China and their CPP was also half the value of overall CPP. This aspect needs to be further examined as collaboration with Chinese researchers could be synergistic.

More than 70% of the output emerged in journals with IF>2 and 70 papers in journals bearing IF>10 and 11 papers in journals with IF>25. The internationally collaborated papers were published in journals with relatively higher IF. Indian researchers have published their research in 592 sources (including journals and 72 proceedings) originating from 23 countries. However, about 94% of the papers were published in journals emerging from top five scientifically advanced countries like USA, England, Netherlands, Germany and Switzerland which suggests that Indian research on Li-ion batteries is connected to the mainstream research in the field. The highest number of papers was published in journals mainly dealing with electric power and electrochemical reactions.

Keyword analysis suggests that the direction / aspects of research worked upon by the scientists included among others; li-ion batteries, anode, cathode, x-ray diffraction, and ionic conductivity, which constitute top ranked five keywords. The emphasis of research keeps changing over different time periods and certain aspects have drastically moved up the rank indicating increasing emphasis and importance. Supercapacitor, graphene, electrochemical performance and EV received attention during the latter half period of the study and moved up the rank. India faces a crucial challenge in so far as very limited resources of lithium in the country. The global lithium reserves too would fall short in decades ahead due to tremendous demand, therefore, it is also required to emphasise on research in environmentally friendly recycling of lithium material in India and at the same time look for an alternative to lithium metal.

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