Scientometrics of rare earths research in India

R. S. Vishnumaya, P. Nishy and S. Mini*

The study attempts to analyse the growth and development of rare earths research in India based on the publication output as reflected in Web of Science (WoS) during 1987–2013. A total of 1,88,877 papers are seen as global research output on rare earths. India secures 7th position with 9457 papers. Indian rare earths papers are analysed bibliometrically to indicate the authorship, collaboration pattern, to identify the major institutions and most relevant journals; apart from identifying the research field or application area of research in rare earths. Recently developed three-dimensional performance indicators are used to rank the productivity of Indian institutions and authors in the field of rare earths research. These studies can help researchers to comprehend the magnitude of rare earths research in India and establish future research directions. The study found that papers having international collaborations are cited more often.

Keywords: Three-dimensional evaluation, India, rare earths, scientific collaboration, scientometrics.

RARE earth elements (REEs) are moderately abundant in the earth's crust, some even more abundant than copper, lead, gold and platinum. While some elements are more abundant than many other materials, because of their geochemical properties, REEs are typically dispersed; most of them are not concentrated enough to make them easily exploitable economically[1]. It was the very scarcity of these minerals that led to the term as 'rare earths'. There are 17 rare earth elements; 15 within the chemical group called lanthanides, plus yttrium and scandium. The lanthanides consist of lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium[2].

There are hundreds of applications for REEs ranging from electronics, medical science, manufacturing, technology, renewable energy and military applications. Global consumption of rare earths was expected to increase at a compound annual growth rate in excess of 5% from 2014 through 2020. China continued to dominate the global supply of rare earths. In 2014, China's rare-earths export quota was 31,000 tonnes, including 27,383 tonnes for light rare earths and 3617 tonnes for heavy rare earths. The United States was once self-reliant in domestically produced REEs, but over the last 15 years has become 100% reliant on imports, primarily from China, because of lower-cost operations and also due to environmental restrictions[3].

In recent years, studies on rare earths have become the nucleus of scientific interest. A variety of tools have been utilized to elucidate the electronic structure, microscopic nature and surface characteristics of rare earth metals, alloys and compounds. At the same time, theoretical models and calculations assist and are aided by the experimental findings. Different extraction and purification techniques, some of them unique, have made the so-called rare earths become more widely available and also of a higher purity than ever. Scientific studies have led to a better understanding of the nature and properties of the rare earths, which, in turn, is expanding their technological applications[4].

Bibliometric methods are used in studies of properties and behaviour of recorded knowledge, for analysis of the structures of scientific and research areas, and for evaluation of research activity and administration of scientific information[5]. Bibliometrics is a statistical analysis of recorded knowledge in articles and books to provide quantitative and qualitative measures. Citation analysis and content analysis are commonly used in bibliometric methods. Bibliometric methods are used to explore the impact of a research field, a set of researchers, or a particular article. Bibliometrics became prominent because of the need to manage the huge investments that were going into the science and technology (S&T) sectors, especially into research and development activities[6]. A good number of scientometric studies have been carried out by different authors on diverse subject fields. Scientometric publications seem to have provided the best available basis for measuring the outputs of an individual scientist as there is good correlation between the eminence of scientists and their sustained research publications[7]. A scientometric analysis by Karpagam to evaluate nano-biotechnology research during 2003–2012 studied the growth, global publications share and citation impact, share of international collaborative papers and contributions of major collaborative partner countries[8]. Bibliometric analysis

The authors are in the CSIR-National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram 695 019, India.
*For correspondence. (e-mail: nishy@niist.res.in)

based on science mapping highlighted the conceptual structure of the intelligent transportation systems (ITS) research field during 1992–2011 (ref. 9). Tanaka and Ho conducted a scientometric study to evaluate the global scientific output of desalination research to assess the characteristics of the research tendencies and research performances based on *WoS* from 1991 to 2008 (ref. 10). Researchers from Bhabha Atomic Research Centre, India analysed the world literature on thorium research during 1982–2004 (ref. 11). They found that 94 countries were involved in thorium research; USA being the top producing country with 1000 authorships (21.11%), followed by India with 498 authorships (10.51%). This paper also indicated that the *Journal of Radio Analytical Nuclear Chemistry* with 181 papers was the most preferred journal by thorium researchers.

In this paper, Indian rare earths research output is studied qualitatively and quantitatively for 1987–2013. As many scientometric studies on rare earths research have not been carried out so far, this study helps to project the worldwide rare earths research, India's share therein, Indian institutions engaged in the research, field domains of rare earths research, the most influential journals in which rare earth research were published by Indian researchers, authorship pattern in the research papers and to visualize the pattern of scientific collaboration in rare earths research in India.

Data and methodology

For the purpose of the study, all records on rare earths research indexed in WoS database during 1987–2013 were downloaded with the following search strategy

> TS = ('rare earth' OR lanthanides OR Scandium OR Yttrium OR Lanthanum OR Cerium OR Praseodymium OR Neodymium OR Promethium OR Samarium OR Europium OR Gadolinium OR Terbium OR Dysprosium OR Holmium OR Erbium OR Thulium OR Ytterbium OR Lutetium) AND CU = India AND PY = 1987–2013.

The search retrieved a total of 9457 records on the subject which were published as journal articles, reviews and conference papers, as these three document types constitute the main channels of communication in science. The records were downloaded to Microsoft Excel, Bibexcel and analysed on the basis of year of publication, authors, authors institutional affiliation & country, source journals and citations received. The results are summarized to map the growth of rare earths research in India and visualize the pattern of collaboration. The visualization and mapping of scientific collaboration are carried out using Pajek and VOS viewer.

We have used bibliometric indicators, viz. total number of publications (P) to measure quantity, citations per paper (i) to indicate impact/quality, eXergy (X) as a second degree indicator combining both quantity and quality, and a third dimensional indicator Zynergy combining quantity (P), quality (i) and consistency (η) for measuring the output apart from the activity index (AI) to characterize the relative research effort.

Results and discussion

Country-wise distribution of rare earths research papers

The global output of rare earths research indexed in *WoS* database during the period of study is found to be 1,88,877 papers. The analysis reveals that a significant share (56%) of rare earths research is concentrated among four countries USA (19.07%), China (17.47%), Japan (10.88%) and Germany (8.86%). The publication productivity of top 10 countries actively involved (based on author affiliation) is depicted in Table 1.

When we consider the quality of research as the impact (i) of research papers, (where i = C/P, C = Citations and P = Papers), the highest impact is for publications from USA, followed by England and Germany. Although China and USA have approximately equal number of papers, the impact of papers from China is less than half (11.79) of USA. India maintains a comparatively good position in terms of both the number of publications and citations. India occupies the 7th position among the most productive countries with 5% of global publication share.

When we assess the quantity and quality together in terms of eXergy (X), where $X = iC$ (ref. 12), countries such as USA, Germany and England occupy the first three positions and India stands at the 8th position.

India's share and activity index

To compare India's performance with the world's performance, we have used the activity index (AI), first

Table 1. Country-wise distribution of rare earths research papers

Country	Papers (P)	Impact ($i = C/P$)	eXergy ($X = i^2P$)
USA	36,026	28.49	29,239,038
Peoples Republic of China	32,990	11.79	4,584,776
Japan	20,545	17.49	6,283,736
Germany	16,737	21.09	7,442,717
France	14,614	20.45	6,114,544
Russia	11,408	8.08	745,180
India	9,457	10.69	1,081,343
England	9,308	27.95	7,273,691
Italy	6,542	20.88	2,852,187
Poland	5,435	9.80	521,761

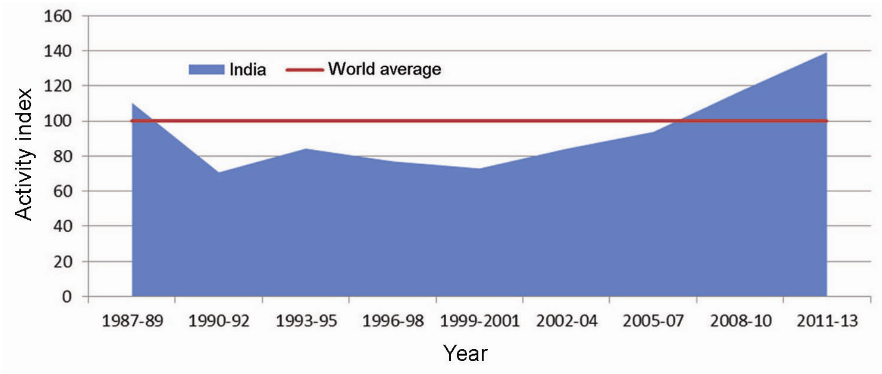

Figure 1. Rare earths research in India during 1987–2013.

suggested by Frame[13] and subsequently used by many bibliometricians[14]. The AI characterizes the relative research effort of a country in a given subject field and is mathematically represented as

$$AI = ((n_{ij}/n_{io})/(n_{oj}/n_{oo})) \times 100,$$

where n_{ij} is the Indian output of papers in a particular field; n_{io} the total Indian output in all fields; n_{oj} the world output of papers in a particular field and n_{oo} is the total world output in all fields.

AI = 100 indicates that the country's research effort in the given field corresponds precisely to the global average. AI > 100 reflects higher activity than the world's average, and AI < 100 indicates lower than average effort dedicated to the field under study. In this article, using the above formula, AI for India and the world is calculated for different years to see the variation in the level of India's performance during the period of study and the same is furnished in Figure 1.

Our analysis shows a rapid growth of Indian rare earths research output from 83 papers in 1987 to 930 papers in 2013 and it accounts for a total of 5% of global research output. The AI of India was slightly higher than the world's average in the early period (1987–1989). However during 1990–2007, the AI of India was less than the global average, then it picked up in 2008 and still continues to be above the global average.

Citation pattern of Indian output

When we see the citation pattern of 9475 rare earths papers from Indian authors, it can be seen that most (37.15%) of the papers received 1 to 5 citations, 18.08% documents received 6 to 10 citations, 15.57% documents received 11 to 20 citations, nearly 11% documents received 21 to 50 citations, more than 2% documents received even more than 50 citations and 15% papers did not receive any citations during the study period. Table 2 shows the citation pattern of Indian rare earth papers at different periods; we can observe that the recent papers are receiving more citations than earlier years. The citations received in first 5 years show that the recent papers are being cited quickly indicating the improved quality of Indian rare earths research over the years.

A close examination of these 68,756 citations reveals that most of them are from India (31%), followed by China (21.7%) and USA (10.27%). CSIR is the highly cited institution of Indian rare earths research (5.86%) followed by Chinese Academy of Sciences (4.77%) and Indian Institute of Technology (IIT) (3.9%). Most citations were received in 2014 (13.24%), 2013 (11.9%) and 2012 (10.23%).

Highly preferred journals

Articles from India on rare earths research were published in a wide range of 1033 journals, with 12.83% in Indian journals, 25.56% in US journals, 21.62% in Netherland journals and 21.51% in England, 7.27% in Switzerland, 4.4% in Germany and 1.04% in Japan. Notably, 30% of these articles were published in journals with impact factor between 2 and 3; another 30% between 1 and 2; 8.45% between 3 and 4; 4.02% in 4 to 5 and around 3% with more than 5 impact factor. The trend of publishing in higher impact factor journals increased over the years.

It was noticed that 80% of the output is concentrated in nearly 25 of the journals and 25% of papers are published in the first 17 journals. *Journal of Alloys and Compounds* published the highest number of articles (307 papers), while *Physical Review B* (178 papers), *Journal of Applied Physics* (170 papers) ranked 2nd and 3rd respectively. While mapping neuroscience research in India, Shahabuddin found that articles drew maximum citations during the first 4–5 years after publication[15]. We used the journal impact factor (JIF) and citations received in the first five years (i_{5yr}) to relate JIF with the citations received for Indian rare earth papers. It is clear from the top 30 journals listed in Table 3 that publishing in higher impact factor journals does not assure a higher number of citations for articles from Indian authors in rare earth research.

Table 2. Citation pattern of rare earths research papers from Indian authors

Total citations	1987–93	1994–98	1999–03	2004–08	2009–13	1987–2013
	Papers as % of total					
0	13.03	14.23	10.38	10.94	20.39	15.31
1 to 5	40.03	34.05	31.72	31.12	42.96	37.15
6 to 10	18.88	16.40	16.87	19.66	17.90	18.08
11 to 20	15.82	17.84	18.24	19.10	11.83	15.57
21 to 50	9.04	13.33	15.79	15.45	6.22	10.93
51 to 75	2.13	2.25	3.68	2.43	0.54	1.79
More than 75	1.06	1.89	3.32	1.30	0.15	1.17
Citations in first 5 years	Papers as % of total					
0	29.92	26.40	18.67	14.58	20.39	20.19
1 to 5	53.46	51.17	46.43	39.76	42.65	44.36
6 to 10	10.37	13.60	18.46	20.18	18.03	17.49
11 to 20	4.92	6.31	9.59	15.36	11.96	11.22
21 to 50	1.20	2.07	5.98	8.85	6.28	5.96
51 to 75	0.13	0.45	0.87	1.26	0.69	0.78

Table 3. Scattering of Indian rare earths research papers in different journals

Journal	Papers (P)	Impact (i)	Impact$_{5yr}$ (i_{5yr})	Impact factor (JIF)
Journal of Alloys and Compounds	307	10.66	7.92	2.999
Physical Review B	178	22.50	12.99	3.736
Journal of Applied Physics	170	11.44	8.39	2.183
Journal of Luminescence	154	14.27	11.94	2.719
Indian Journal of Chemistry Section A	151	4.36	2.26	0.851
Physica B – Condensed Matter	145	9.26	7.28	1.319
Journal of Magnetism and Magnetic Materials	140	9.54	5.99	1.97
Asian Journal of Chemistry	132	0.83	0.55	4.587
Bulletin of Materials Science	126	8.09	3.12	1.017
Materials Letters	123	12.72	5.82	2.489
Materials Chemistry and Physics	122	12.38	7.11	2.259
Spectrochimica Acta Part A – Molecular and Biomolecular Spectroscopy	120	10.63	6.54	2.353
Journal of Physics – Condensed Matter	119	14.60	8.96	2.346
Journal of the Indian Chemical Society	116	2.20	0.93	0.173
Solid State Communications	110	11.11	6.22	1.897
Materials Research Bulletin	107	11.93	6.15	2.288
Journal of the Geological Society of India	102	3.88	1.93	0.596
Tetrahedron Letters	94	24.45	15.33	2.379
Optical Materials	91	16.97	11.6	1.981
Indian Journal of Pure & Applied Physics	86	3.49	2.26	0.766
Journal of Materials Science	85	8.60	4.54	2.371
Applied Physics Letters	81	16.70	11.22	3.302
Journal of Physics and Chemistry of Solids	80	13.16	6.56	1.853
Ceramics International	80	6.88	4.79	2.605
Journal of Radioanalytical and Nuclear Chemistry	74	6.39	4.00	1.034
Pramana – Journal of Physics	70	4.60	2.41	0.649
Journal of Solid State Chemistry	64	12.36	6.73	2.133
Journal of the American Ceramic Society	61	12.49	8.36	2.61
Radiochimica Acta	59	6.61	4.31	1.014
Journal of Thermal Analysis and Calorimetry	57	9.40	7.33	2.042

Performance of research institutes

A total of 2300 institutions from India published 9457 papers in rare earths during the period of study. It is observed that the research activities were concentrated mainly in 25 institutes which accounts for more than 50% of publications. Table 4 compares these top institutes on quantity (P), quality (i) and total performance (eXergy). It is clear from Table 4 that, as far as publication output is concerned, institutes of national importance such as Bhabha Atomic Research Centre (BARC), Mumbai (886); Indian Institute of Science (IISc), Bengaluru (410); National

Table 4. Institution-wise distribution of rare earths research papers in India

Institute	Papers (P)	Impact (i)	Impact_{5yr} (i_{5yr})	eXergy (X)	Consistency (η)	z-index (z)
BARC	886	9.67	6.42	82,914	0.27	28.20
IISc	410	17.65	9.25	127,742	0.30	33.65
CSIR–NIIST	358	16.61	10.13	98,724	0.35	32.68
TIFR	312	12.68	7.16	50,160	0.24	22.95
Sri Venkateswara University	293	14.20	9.61	59,092	0.43	29.38
IIT Madras	288	8.47	5.47	20,638	0.33	18.96
IGCAR	257	10.00	5.80	25,720	0.24	18.42
CSIR–CGCRI	245	10.81	6.94	28,642	0.37	21.89
CSIR–IICT	230	21.07	13.58	102,103	0.43	35.19
BHU	202	11.78	7.93	28,042	0.39	22.10
IIT Kharagpur	198	12.47	6.56	30,813	0.29	20.86
IIT Delhi	180	8.95	5.66	14,418	0.31	16.46
CSIR–NPL	176	10.59	7.78	19,720	0.31	18.23
IIT Bombay	173	10.64	6.66	19,591	0.31	18.26
National Institute Technology	151	5.59	5.17	4,717	0.34	11.75
Osmania University	148	8.10	4.39	9,714	0.33	14.81
IIT Kanpur	145	14.32	9.48	29,751	0.30	20.71
University of Delhi	140	9.40	5.99	12,370	0.42	17.35
Anna University	138	8.75	4.77	10,557	0.21	13.06
IACS	127	16.42	11.03	34,230	0.40	23.99
JNCASR	120	22.18	14.93	59,008	0.36	27.59
CUSAT	120	10.60	5.67	13,483	0.37	17.13
CSIR–NCL	118	19.58	10.22	45,221	0.35	25.09
SINP	118	9.06	5.42	9,684	0.21	12.59
MG University	107	10.37	3.91	11,515	0.11	10.94

Institute for Interdisciplinary Science and Technology (CSIR-NIIST), Thiruvananthapuram (358) and Tata Institute of Fundamental Research (TIFR), Mumbai (312) are the leading organizations in rare earths research in India.

Figure 2 shows the quality–quantity graph (citation versus impact) of the 30 top producing institutes from India. Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bengaluru is seen as having publications with high impact (i) followed by Indian Institute of Chemical Technology (CSIR-IICT), Hyderabad and National Chemical Laboratory (CSIR-NCL), Pune.

The 3D evaluation recently proposed by Prathap[16] is used to rank institutions in rare earths research in India combining consistency (η) with quantity (P) and quality (i). The exergy indicator $(X) = iC = i^2P$, a robust second order performance indicator is arguably a better proxy for performance. Apart from X, an additional indicator $E = \sum C_k^2$, where $k = 1$ to P, also appears as a second order indicator. The simple ratio of X to E can be viewed as the third component of performance, namely, the consistency term $(\eta) = X/E$. Perfect consistency ($\eta = 1$, i.e. when $X = E$) is a case of absolutely uniform performance; that is, all papers in the set have the same number of citations, $C_k = c$. The greater the skew, the larger is the concentration of the best work in very few papers of extraordinary impact. The inverse of consistency thus becomes a measure of concentration.

It is observed that IISc, CSIR-IICT, CSIR-NIIST and BARC occupy the top positions based on eXergy. When we analyse the consistency (η) of these institutions, CSIR-IICT obtains first place followed by Sri Venkateswara University and University of Delhi. However, for a complete evaluation of publication activity, the three primary components of quantity (P), quality (i) and consistency (η) can be used together, yielding a Zynergy indicator and z-index computed as $Z = \eta X = \eta^2 E$ and $z = Z^{1/3}$ respectively. While analysing the institution-wise distribution of rare earths papers by z-index, CSIR-IICT, IISc and CSIR-NIIST occupy the first three positions.

Apart from R&D organizations and institutes of national importance, universities are also engaged in rare earths research contributing 12% of the output. Sri Venkateswara University, Banaras Hindu University and Osmania University are in the leading positions in this category.

Subject categories

Based on the classification of subject categories in *WoS*, the publication output on rare earths research in India was dispersed into 132 *WoS* subject categories. These categories were mapped to the 32 OECD subject categories, a hierarchical classification scheme, in which science and social science are separated into six major subject categories within which there are several minor subject categories. Table 5 shows the subject-wise breakup of rare earths articles published from India. The highest number

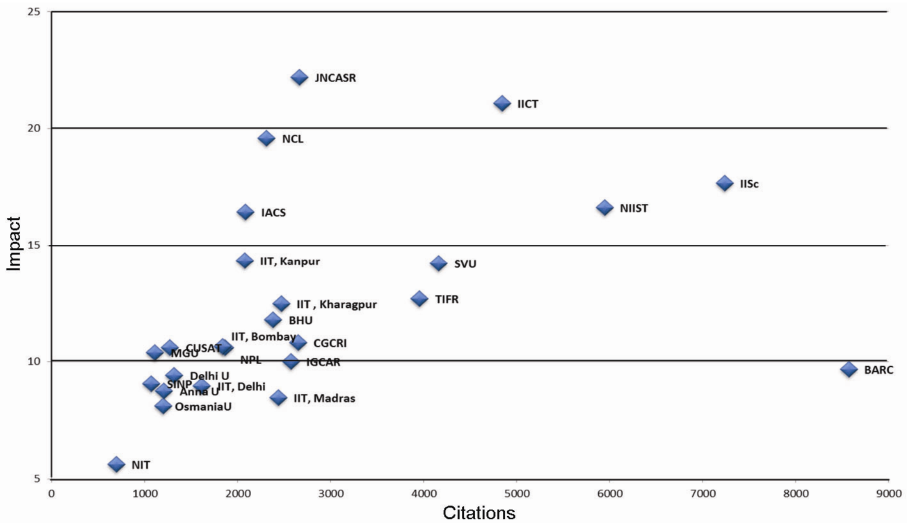

Figure 2. Major Indian institutes in rare earths research.

Table 5. Indian rare earths research in different disciplines of S&T

Discipline	Papers (*P*)	Impact (*i*)	Impact$_{5yr}$ (i_{5yr})	eXergy (*X*)
Chemical sciences	3773	12.17	7.50	559,048
Physical sciences	3613	9.48	6.06	324,963
Materials engineering	2735	10.53	6.51	303,100
Earth and related environmental sciences	495	10.95	5.46	59,324
Other engineering and technologies	418	7.82	4.89	25,534
Mechanical engineering	410	6.40	3.85	16,794
Electrical engineering, electronic engineering, information engineering	288	3.67	2.16	3,879
Civil engineering	278	13.05	10.60	47,347
Chemical engineering	275	13.17	8.06	47,731
Clinical medicine	198	11.84	6.83	27,749
Environmental engineering	166	10.94	8.00	19,867
Biological sciences	158	9.92	5.67	15,561
Other natural sciences	108	4.25	2.69	1,951
Basic medicine	64	8.63	5.56	4,761
Mathematics	62	4.37	2.55	1,185
Environmental biotechnology	25	23.60	15.76	13,924
Computer and information sciences	23	4.43	1.39	452
Industrial biotechnology	16	16.00	14.63	4,096
Health sciences	15	5.93	3.13	528
Medical engineering	10	17.00	15.30	2,890
Others	13	5.15	2.23	345

of publications is in chemical sciences discipline (3773), followed by physical sciences (3613) and materials engineering (2735). Articles in environmental biotechnology, medical engineering, industrial biotechnology and chemical engineering have higher impact (*i*) than other subject categories.

Authorship pattern

There are 16,000 authors contributing 9457 rare earth papers, out of which 364 are single-authored papers with an impact (*i*) of 8.95. There are 2139 two-authored papers with impact of 9.6, 2451 papers from three authors received an impact of 10.09. There are 87 publications authored by more than 10 authors with impact of 16.22. It is observed that as the number of authors increased, the impact (*i*) also increased.

Table 6 presents the leading Indian authors ranked according to *z*-index. Rao from JNCASR tops the list based on quantity (102 papers) as well as impact (32.41) followed by Reddy from CSIR-NIIST, Yadav and Tyagi from BARC, Jayasankar from Sri Venkateswara University and Reddy from CSIR-IICT.

Table 6. Most prolific Indian authors in rare earths research in the order of *z*-index

Authors	Papers (*P*)	Impact (*i*)	Impact$_{5yr}$ (i_{5yr})	eXergy (X)	Consistency (η)	*z*-Index (*z*)
Rao, C. N. R., JNCASR	102	32.41	18.18	107,153	0.34	33.28
Reddy, M. L. P., NIIST	86	22.14	15.86	42,154	0.54	28.33
Yadav, J. S., IICT	73	21.51	12.95	33,766	0.52	26.06
Jayasankar, C. K., SV University	87	20.36	12.11	36,051	0.48	25.86
Reddy, B. V. S., IICT	57	20.70	12.65	24,428	0.59	24.38
Rai, S. B., BHU	70	17.26	12.14	20,847	0.55	22.53
Rao, T. P., NIIST	52	20.52	9.65	21,894	0.46	21.52
Moorthy, L. R., SV University	59	13.39	11.47	10,578	0.56	18.08
Manchanda, V. K., BARC	76	11.46	9.88	9,982	0.51	17.24
Mohapatra, P. K., BARC	77	11.12	9.77	9,516	0.52	17.08
Buddhudu, S., SV University	61	13.02	6.87	10,335	0.47	16.94
Tyagi, A. K., BARC	96	13.67	9.70	17,931	0.25	16.48
Damodaran, A. D., NIIST	62	10.85	4.23	7,305	0.49	15.34
Dhar, S. K., TIFR	64	12.59	7.02	10,151	0.34	15.10
Nigam, A. K., TIFR	51	12.94	7.61	8,541	0.28	13.37
Choudhary, R. N. P., IIT Kharagpur	55	10.22	5.91	5,743	0.39	13.14
Rao, P. R. V., IGCAR	51	8.45	6.31	3,642	0.58	12.80
Dhoble, S. J., Nagpur University	64	10.13	8.06	6,561	0.31	12.68
Kotru, P. N., Jammu University	69	8.07	2.93	4,496	0.45	12.66
Sanyal, S. P., Barkatullah University	52	7.13	4.54	2,647	0.42	10.36

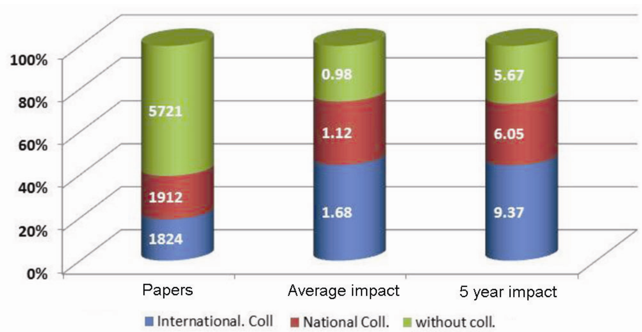

Figure 3. Collaboration pattern of Indian rare earths research papers.

Scientific collaboration

Collaboration is often a critical component of research in the world of 'big science', which involves large-scale projects dominated by complex problems, rapidly changing technology, the dynamic growth of knowledge and highly specialized expertise[17]. The historical trend toward specialization in science has brought a need for multidisciplinary collaboration to bring together the knowledge, skills, and abilities required for the advancement of research[18]. No individual scientist can possess all the knowledge, skills or time needed to make theoretical or applied contributions in more than a very narrow area of research such as rare earths. Melin and Persson discussed the relationship between collaboration and co-authorship, the nature of bibliometric data and exemplifies how they can be refined and used to analyse the various aspects of collaboration[19].

It is observed that 60.48% papers are research output of single organization, 20.22% are collaborative output from Indian institutions and only 19.30% are results of international collaboration. It could be noticed that papers with foreign collaboration have a higher impact (*i*) than single institutional papers and domestic collaboration documents. It was also observed that the domestic collaboration papers received more citations immediately after publication than individual institutional papers (Figure 3).

International collaboration: Figure 4 shows the collaboration network of foreign countries with India in rare earths papers. The total number of co-authored papers with foreign authors is 1824 papers. The top three collaborating countries USA, Germany and France have contributed 352, 266 and 205 papers respectively (Table 7). It was also noticed that collaborative papers with Australia fetched the highest citations followed by USA and Switzerland. The collaborative papers with Spain and Switzerland received more impact (i_{5yr}) during the initial 5 years.

Institutional collaboration: The institutional collaboration within India and abroad is projected in Figure 5. Each colour represents a cluster of collaborated institutes with a particular Indian research institute. From the study, it is observed that the highest collaboration occurred in BARC with 47 institutes, followed by CGCRI with 21 institutes, IISc with 14 institutes, TIFR with 13 other institutes and CUSAT with 12 institutes. BARC collaborated with Saha Institute of Nuclear Physics (21 papers), with IIT Bombay (19) and with University of Munster, Germany (18). The cluster of CGCRI depicts 31 papers with University of Malaya (Malaysia), 16 papers with Sri Venkateswara University and 12 papers with University of Southampton (England). IISc has produced 32 papers in partnership with JNCASR. TIFR has brought out 28 papers with IIT Bombay and 25 papers with University of

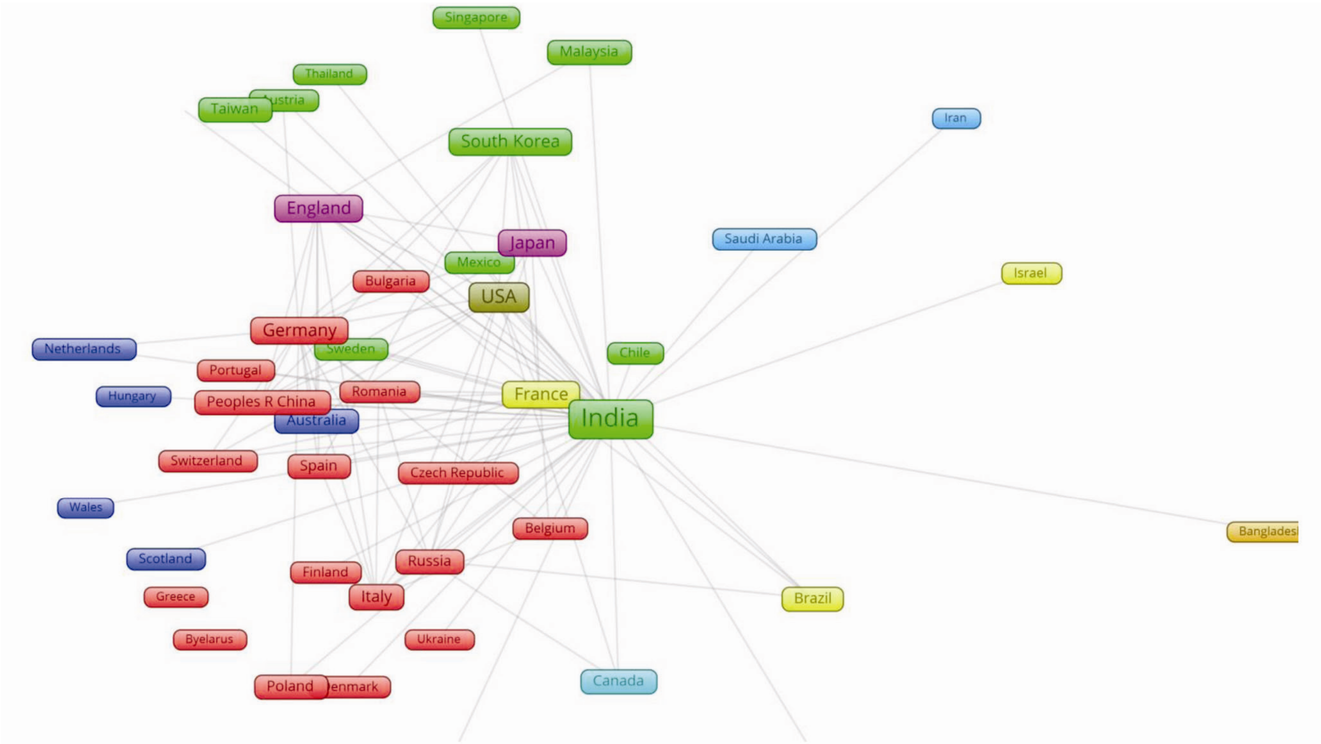

Figure 4. International collaboration network among countries.

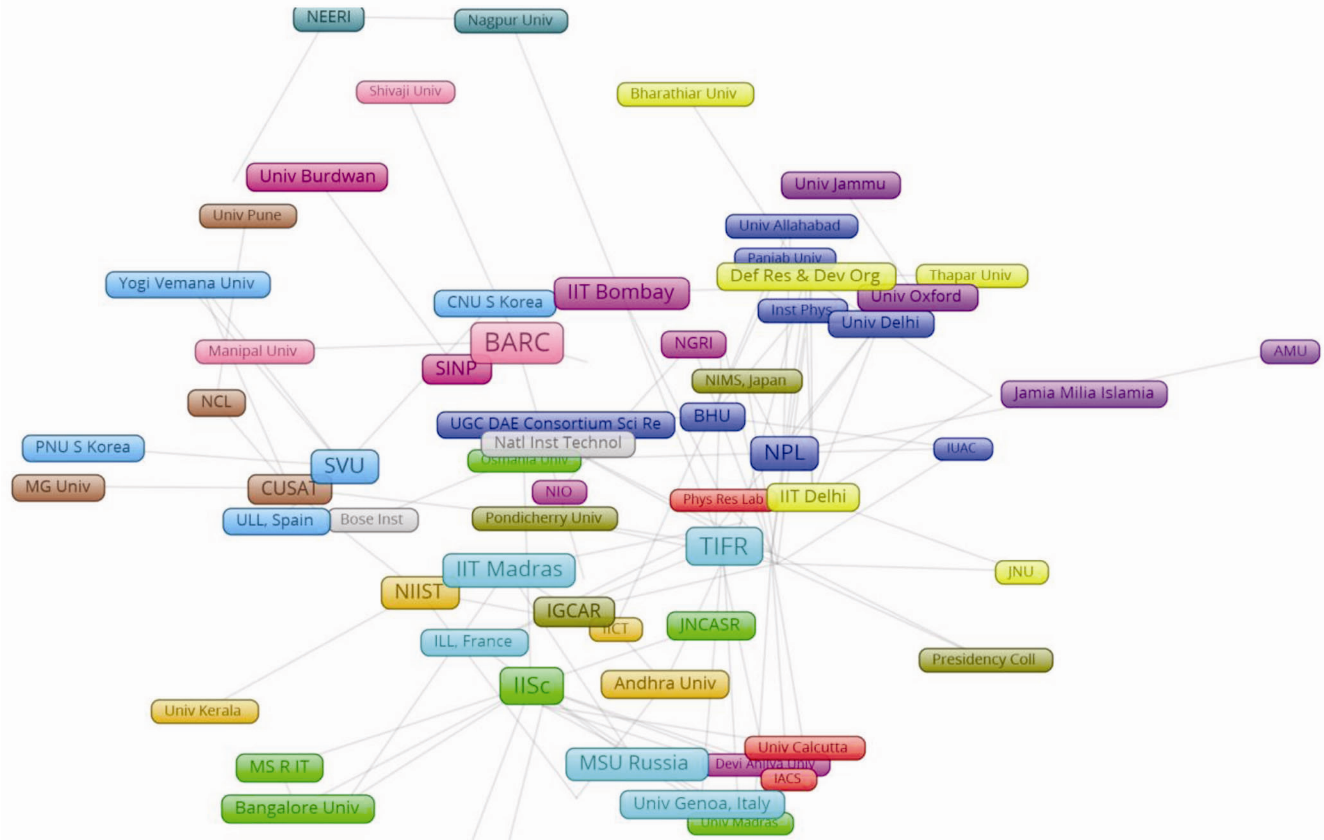

Figure 5. Collaboration network among different research institutions.

Table 7. International collaboration pattern of Indian rare earths papers

Country	Papers (P)	Impact (i)	Impact$_{5yr}$ (i_{5yr})
USA	352	21.29	12.69
Germany	266	18.15	11.82
France	205	16.61	11.33
Japan	202	14.19	9.43
England	200	14.10	8.79
South Korea	185	10.47	9.08
Italy	108	13.12	9.13
Brazil	67	12.64	9.27
Spain	63	19.19	14.87
Russia	61	8.23	6.05
Canada	57	19.46	12.16
Malaysia	54	6.93	6.11
Peoples Republic of China	54	17.06	11.44
Taiwan	51	13.73	9.16
Australia	44	21.57	13.55
Poland	35	15.23	10.77
Netherlands	30	17.17	12.23
Switzerland	28	19.93	14.82
Saudi Arabia	27	8.00	8.00
Next 60 countries	377	13.78	9.12
Total	1824	14.37	9.37

Genoa, Italy. Among the institutes from Kerala, CUSAT has 18 collaborative papers with CSIR-NIIST followed by MG University with 15 papers during the study period.

Conclusion

The scientometric study of rare earths research identified a total of 188,877 papers as global output published during a period of 27 years (1987–2013). It is observed that USA is the predominant performer in the field by way of quantity (p), impact (i) and performance (eXergy). India has also made a significant headway being the 7th most active country, but not as striking as other leading countries. During the period under reference, India published 9457 papers in a broad range of 1033 journals. Articles published in *Tetrahedron Letters* have the highest impact (i) followed by *Physical Review B* and *Journal of Luminescence*. The publication output of rare earths research in India is segmented into chemical sciences, physical sciences and materials engineering, etc. BARC is found to be the most contributing institution followed by IISc and CSIR-NIIST. Scientific collaboration in rare earths is greater within Indian research institutes; however, international collaboration papers received higher impact (i) than single institutional or domestic collaborative papers.

1. Hedrick, J. B., Minerals Yearbook – Rare Earths. In *US Geological Survey Minerals Yearbook – 2007*, 2010, pp. 1–17.
2. Humphries, M., *Rare Earth Elements: The Global Supply Chain*, 2010.
3. US Geological Survey. *Mineral Commodity Summaries 2015*, Virginia, 2015.
4. Subbarao, E. C., *Science and Technology of Rare Earth Materials*, Academic Press, New York, 1980.
5. Patra, S. K., Bhattacharya, P. and Verma, N., Bibliometric study of literature on bibliometrics. *DESIDOC Bull. Inf. Technol.*, 2006, **26**(1), 27–32.
6. Prathap, G., Bibliometrics – problems and promises. *Curr. Sci.*, 2015, **108**(2), 147–148; doi: 10.1038/nature.2012.11583.
7. Price, D. J. D. S., *Little Science, Big Science – And Beyond*, Columbia University Press, 1986.
8. Karpagam, R., Global research output of nanobiotechnology research: a scientometrics study. *Curr. Sci.*, 2014, **106**, 1490–1499.
9. Cobo, M. J., Chiclana, F., Collop, A., de Ona, J. and Herrera-Viedma, E., A bibliometric analysis of the intelligent transportation systems research based on science mapping. *IEEE Trans. Intell. Transp. Syst.*, 2014, **15**, 901–908; doi: 10.1109/TITS.2013.2284756.
10. Tanaka, H. and Ho, Y.-S., Global trends and performances of desalination research. *Desalin Water Treat*, 2011, **25**(1–3), 1–12; doi:10.5004/dwt.2011.1936.
11. Kademani, B., Kumar, V. and Sagar, A., World literature on thorium research: a scientometric study based on *Science Citation Index*. *Scientometrics*, 2006, **69**(2), 347–364.
12. Prathap, G., Quasity, when quantity has a quality all of its own – toward a theory of performance. *Scientometrics*, 2011, **88**, 555–562.
13. Frame, J. D., Mainstream research in Latin America and Caribbean. *Interciencia*, 1977, **2**, 143–147.
14. Garg, K. C. and Padhi, P., Scientometrics of laser research literature as viewed through the *Journal of Current Laser Abstracts*. *Scientometrics*, 1999, **45**(2), 251–268.
15. Shahabuddin, S. M., Mapping neuroscience research in India – a bibliometric approach. *Curr. Sci.*, 2013, **104**(12), 1619–1626.
16. Prathap, G., Quantity, quality, and consistency as bibliometric indicators. *J. Assoc. Inf. Sci. Technol.*, 2014, **65**(1), 214; doi: 10.1002/asi.23008.
17. Galison, P. and Hevly, B. W., *Big Science_ The Growth of Large-Scale Research*, Standford University Press, 1992.
18. Stevens, M. J. and Campion, M. A., The knowledge, skill, and ability requirements for teamwork: implications for human resource management. *J. Manage.*, 1994, **20**(2), 503–530; doi: 10.1177/014920639402000210.
19. Melin, G. and Persson, O., Studying research collaboration using co-authorships. *Scientometrics*, 1996, **36**(3), 363–377; doi: 10.1007/BF02129600.

Received 2 September 2015; revised accepted 3 November 2015

doi: 10.18520/cs/v110/i7/1184-1192