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Mathematics research in India: a scientometrics and complex network analysis

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Abstract. Over the past three decades, there has been a noticeable growth in both the quantity and quality of scientific research in India. In recent years, India's growing prominence on the global map of research productivity has become highly visible. Numerous scientometrics studies have been reported for various fields in India such as computer science, nanoscience, nanotechnology, artificial intelligence, solar cells, and dentistry among others. However, there is a lack of scientometric research in the domain of mathematics within India, despite its crucial role in propelling advancements across various disciplines. Furthermore, research collaboration has emerged as an important factor in accelerating the progress of mathematics research in a country since the 20th century. Therefore, studying collaboration trends becomes an essential component of scientometrics. In this paper, we comprehensively analyze the state of mathematics research in India, including collaboration trends, using methods from scientometrics and complex network analysis. Scientometrics offers an overview of the nature of mathematics research being undertaken, while complex network analysis reveals the dynamics and structural variation of research collaborations at the country and institutional level across various temporal periods. The findings provide insights into the development and collaboration trends of mathematics research in India from 2001 to 2021. There has been an exponential increase in publications since 2015, with approximately 20% of mathematics research conducted in India appearing to be associated with physics research. In terms of research collaborations, there has been a notable increase in collaborations between India and several countries including the USA, China, Saudi Arabia, and Turkey. However, an analysis of institutional collaboration networks suggests that these collaborations tend to be small-scale research.

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1 Introduction

A 2016 Report by Springer Nature Index study commissioned by the Confederation of Indian Industry, showed the growth of Indian science productivity based on the Nature Index [1]. The index is a combination of Nature Publishing Group, Springer Science & Business media as well as Macmillan Education and Palgrave Macmillan. This index, based on 68 high-quality science journals, positioned India 13th worldwide among global countries. This report provided a different insight into the status of research in India, which was perceived as lagging behind leading nations such as the USA, China, and European countries.

Recently, the US National Science Foundation report on Science and Engineering Indicators 2022, also demonstrated the spectacular growth of Indian science into the Top 8 in the global arena with a 2-3% contribution using a Scopus-based database. This is a surprising development as a 2021 United Nations Educational, Scientific and Cultural Organization (UNESCO) Science Report on India highlighted the stagnation of gross domestic expenditure on research and development (GERD) at 0.7% of gross domestic product (GDP), which is the lowest among the BRICS nations. Brazil, China and Russia are using more than 1% of their GDP in GERD, with China even reaching the Organisation for Economic Co-operation and Development (OECD) thresholds. However, Gangan [2] had projected a bright future for India's Science which he believe is achievable.

Mathematics in India as a human endeavor has evolved from ancient times to the modern era. From a historical perceptive, readers are referred to some recently published books [3-5]. In the modern context of scientometrics, Arunachalam [6] was the first to study mathematics research in India using the American Mathematical Society (AMS) MathSci database of more than 17000 papers indexed for the period 1988 – 1998. His findings and discussions were due to his keen sharp eye and insights. In the study, he reported that among the 134 cities/towns, Calcutta published the largest number of papers in mathematics. Further, nearly 70% of these papers were published in non-Indian journals such as journals from USA, UK and Netherlands. He found that most papers in high-impact journals were on physics-related subjects which carried affiliations from research institutions such as the Department of Atomic Energy. Furthermore, he observed a significant growth of international collaboration with the USA, Canada, and Germany. As noted in that paper, although India had a long traditional history of mathematics, it was only in the recent century or so, that it has shown prominence in various branches of mathematics. In this context, several important articles have been written about the achievements of mathematics research within India [7-9]. Some studies highlighted the significant roles played by various academic institutions such as the Tata Institute of Fundamental Research (TIFR) and Indian Statistical Institute (ISI), as well as the eminent researchers from those institutions [6,7,9].

Over the last two decades or more, we have witnessed a rapid growth of international collaborations [10-15] Two critical factors at play include key performance targets for academics to achieve international visibility and global rankings of universities [13]. Aside from that, there is a growing interest in the study of research collaborations by utilizing scientometrics. The exploration of research collaborations offers a deeper understanding of various aspects of research areas, including research themes [16], research trends [17], and internationalization within the research areas [18]. As far as we know, no research has examined the development of mathematics research in India from a scientometric perspective since Arunachalam's work [6]. Furthermore, no studies have investigated research collaboration trends in mathematics research within India. Hence, in this background of the ascending of Science in India, we aim to revisit Arunachalam's [6] study by using the Web of Science (WoS) database. Our objective is to analyse the growth and collaboration trends of mathematics research in India over the first two decades of the 21st century. In this paper, besides conducting descriptive statistical analysis using scientometrics to explore the nature of mathematics research being undertaken, we also employ complex network analysis to explore the research collaboration trends within mathematics research in India from 2001 – 2021.

2 Methodology

2.1 Data Collection

The data was collected from the WoS (https://www.webofscience.com) by searching for publications categorized under the following WoS categories: "Mathematical & Computational Biology", "Mathematics", "Mathematics, Applied", "Mathematics, Interdisciplinary Applications", "Physics, Mathematical", "Psychology, Mathematical", and "Social Sciences, Mathematical Methods". These categories encompass all publications that are related to mathematics. Subsequently, we filtered out publications with the country of affiliation "India". The filtered search returned 57550 publications of various types. By using the "Export" feature in WoS, we retrieved the full record of the publications for further analysis. Aside from that, we obtained the summaries of the search records, such as affiliations, authors, countries, research areas, and WoS categories by using the "Analyze Results" feature in WoS. The "Citation Report" allowed us to acquire the number of publications and citations per year for each paper. The data was obtained on 13 June 2023.

2.2 Complex Network Analysis

Complex network analysis is a research field that delves into the studies of complex networks, where these networks are regarded as interconnected systems with intricate properties. In general, networks are composed of nodes representing various entities, and edges describing the relationship or interactions between these entities. The specifications of the nodes and edges differ from network to network. The absence and presence of directions on the edges distinguish networks as undirected or directed. The interactions between nodes are considered symmetrical in undirected networks. Furthermore, networks can be categorized as either weighted or unweighted based on whether edge weights are considered. Edge weights are used to capture the frequency of interactions between nodes.

Complex network analysis was widely used in scientometrics. For instance, Zhu & Guan [19] studied the knowledge structure in the research field of service innovation by investigating the network characteristics of keywords, author collaboration, and subject category networks. Other research works that utilized complex network analysis also provided interesting findings in terms of research collaboration, research productivity, and research trends [20-23].

In this paper, two categories of undirected and weighted networks, namely the Country Collaboration Networks and Institutional Collaboration Networks, were constructed to study the collaborative attributes of mathematics research in India. The networks are considered undirected as research collaborations are viewed as bi-directional endeavours.

In the Country Collaboration Networks, nodes represent the countries with which Indian affiliations engaged in collaborative mathematics research. It must be noted that Indian affiliations are excluded from these networks. The edges between nodes are established whenever two countries collaborate in producing a publication in mathematics research. The edge weights denote the frequency of collaborations between the two connected countries. In the context of the Institutional Collaboration Networks, nodes refer to academic institutions that have contributed to publications in mathematics research. Edges denote the collaborative connections between two such institutions, with the edge weights indicating the frequency of the collaborations.

2.2.1 Network Properties

Five network properties were used to analyse the complex networks: giant component, network density, degree centrality, eigenvector centrality, and average clustering coefficient. The subsequent paragraphs lay out the details of these metrics.

A giant component in a network is a connected component of the network that includes a substantial portion of the total nodes comprising the network. The network components were obtained by using a depth-first search algorithm [24].

Given an undirected network $G(V, E)$ with V and E as the sets of nodes and edges in the network, network density is a measure to quantify the interconnectedness of the nodes within a network. For undirected networks, the network density is defined as

$$D = \frac{2|E|}{|V|(|V| - 1)}, \tag{1}$$

where $|E|$ and $|V|$ are the total number of edges and nodes in the network, respectively.

Let $\mathbf{A} = (a_{i,j})$ as the adjacency matrix of a network, where $a_{i,j} = 1$ when there exists an edge between nodes i and j, and $a_{i,j} = 0$ in the absence of such an edge, the degree of a node in a network is the number of edges connected to that node [25]. The degree of node i in a network with n total nodes is defined as

$$k_i = \sum_{j=1}^{n} \mathbf{A}_{ij} . \tag{2}$$

Eigenvector centrality is used to quantify the influence of a node within networks [26]. The relative centrality score of node i, x_i, is defined as

$$x_i = \frac{1}{\lambda} \sum_{m \in V} a_{i,m} x_m , \tag{3}$$

where λ is a constant. By defining $\mathbf{x} = (x_1, x_2, ...)$, eq. (3) can be rewritten as

$$\lambda \mathbf{x} = \mathbf{A}\mathbf{x} \tag{4}$$

which is an eigenvector equation with $\mathbf{x}$ as an eigenvector of $\mathbf{A}$ with eigenvalue λ. The i^{th} element in $\mathbf{x}$ is the relative eigenvector centrality score of node i in the network. Eigenvector centrality ranges from zero to one. Generally, a node with high eigenvector centrality tends to be connected to nodes with high eigenvector centrality. This indicates that a highly influential node will consistently link with other influential nodes.

Average clustering coefficient of a network is the average of the local clustering coefficients across all nodes in the network. The local clustering coefficient of node i for undirected networks is defined as [27]

$$C_i = \frac{2\left|\{e_{jk} : v_j, v_k \in N_i, e_{jk} \in E\}\right|}{k_i(k_i - 1)}, \tag{5}$$

where e_{jk} is the edge connecting j and k, N_i is the set of neighbourhood nodes of i, and k_i is the degree centrality of node i. The average clustering coefficient ranges from zero to one. Typically, a high average clustering coefficient indicates that the network has a notable level of clustering behaviour.

3 Analysis of the Mathematics Research in India

3.1 Number and Type of Publications

From 2001 to 2021, the total number of publications is 57550, with over 480000 citations. It must be noted that the citations were dated 13 June 2023, and only citations which exclude self-citations and cited by WoS-indexed publications were included. In general, the number of publications shows a steady growth from year 2001 to 2014 (see Figure 1). From 2015 onwards, the number of publications grew exponentially. The total number of publications from 2015 to 2021 is 36519, which is 70% more than the total number of publications from 2001 to 2014 (21031). In terms of citation, the publications in the year 2009 are the most cited, where the publications received 30004 (approximately 6.17% of total number of citations) citations.

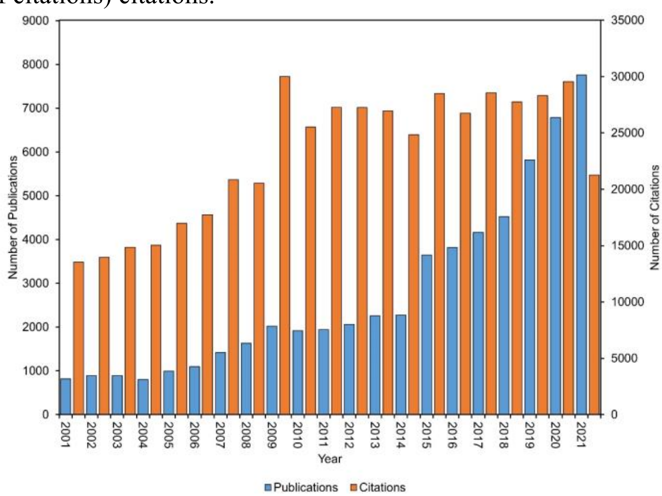

Fig. 1. Number of publications with India affiliations and the number of citations of those publications per year.

Table 1 shows a breakdown of types of publications among the total publications of 57550 papers. It must be highlighted the record count exhibits double counting, wherein some of the publications were simultaneously categorized by WoS as multiple document types. This table reveals that most of the mathematics research works fall into the categories of journal articles and proceeding papers, with journal articles as the predominant type of publications (approximately 88% of the total publications). The remaining types of publications are book chapters, review articles, and editorial materials, which collectively encompass less than 5% of the total publications.

Table 1. Types of publications spanning the period of 2001 to 2021.

Document Types	Record Count	% of 57550
Article	50888	88.42
Proceeding Paper	6088	10.58
Book Chapters	1434	2.49
Review Article	571	0.99
Editorial Material	427	0.74

3.2 Research Areas Associated with Mathematics Research

In the broader context of research areas within mathematics, there are 43789 publications (approximately 79% of total publications), pertain to the research area of mathematics. A notable 11% of the total publications, corresponds to 6507 publications falling under the domain of Mathematical Computational Biology. Furthermore, a small proportion of publications, numbering 728 and constituting around 1.2% of total publications, is classified as Mathematical Methods in Social Sciences. However, for publications exclusively under the "Mathematics", "Mathematical Computational Biology", and "Mathematical Methods in Social Sciences", there are 29094, 1493, and 15 publications, respectively.

Table 2. Research areas of the total publications spanning the period of 2001 to 2021. Research areas that are marked by * are considered research areas under mathematics.

Research Areas	Numbers of Publications	% of 57550
Mathematics*	43789	76.09%
Physics	11364	19.75%
Computer Science	7451	12.95%
Mathematical Computational Biology*	6507	11.31%
Engineering	5045	8.77%
Mechanics	2692	4.68%
Biochemistry Molecular Biology	1451	2.52%
Operations Research Management Science	1271	2.21%
Life Sciences Biomedicine Other Topics	1081	1.88%
Chemistry	934	1.62%
Automation Control Systems	914	1.59%
Astronomy Astrophysics	876	1.52%
Mathematical Methods in Social Sciences*	728	1.27%

Mathematics research in India was associated with 75 non-mathematics research areas. However, from Table 2, it can be observed that none of the research areas displayed an exceptionally strong association with mathematics research. Physics has the highest level of association, with approximately 20% of the mathematics research publications in India being linked to Physics.

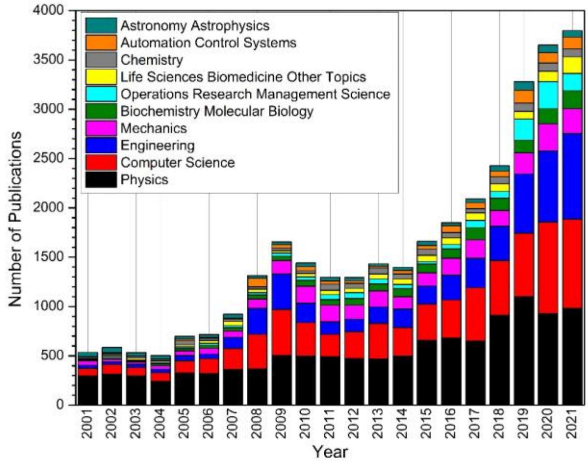

Fig. 2. Top 10 non-mathematics research areas that were associated with mathematics research in India.

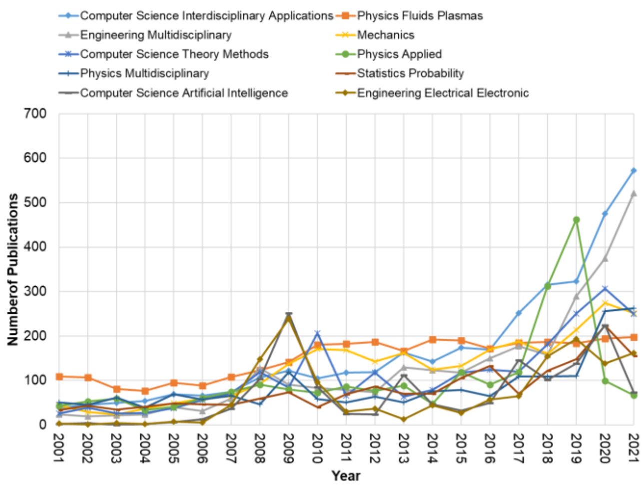

Fig. 3. Top 10 non-mathematics WoS categories that were associated with mathematics research in India.

In Figure 2, the trend in associations between mathematics research and various non-mathematics research areas in India over the last two decades can be observed. Most of the research areas exhibit marginal growth in their connections with mathematics research during this period, except for Physics, Computer Science, and Engineering. Both Computer Science and Engineering show a surge in associations from 2007 to 2009, followed by a drastic decline in the subsequent two years. A closer examination of the WoS categories during this period revealed that this fluctuation was primarily due to the substantial changes in the research in Computer Science Artificial Intelligence and Engineering Electrical Electronic (see Figure 3).

Subsequently, mathematics research in India displays exponential growth in its associations with Physics, Computer Science, and Engineering starting from the year 2014. Mathematics research associated with Physics reached its peak in 2019. The surge in multidisciplinary engineering research and interdisciplinary computer science applications research in India over the past 5 years contributes to a significant increase in the association of mathematics research in computer science and engineering.

3.3 International Collaborations

In terms of international collaboration, researchers affiliated with institutions in India collaborated with 150 countries in mathematics research, with approximately 50 out of the 150 countries participating in over 100 joint research endeavours with India during two decades. Figure 4 depicts the top 10 countries that have engaged in collaborative research in mathematics with India.

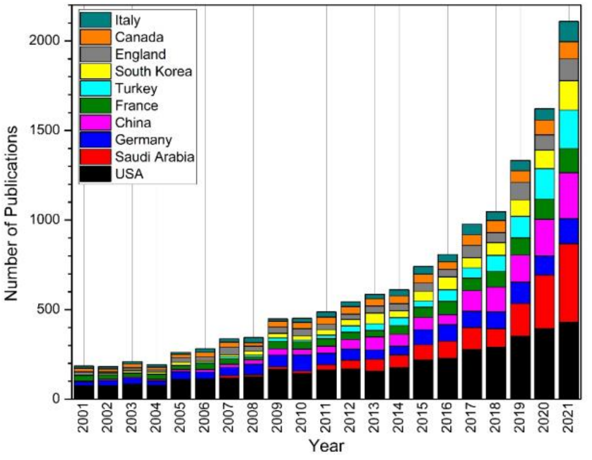

Fig. 4. Top 10 countries that collaborated with India in mathematics research.

In general, researchers from India most frequently collaborated with researchers from the USA, with the number of publications at least double that of other countries except for Saudi Arabia in the years 2020 and 2021. While most of the Top 10 countries exhibited linear growth, the USA, Saudi Arabia, China, and Turkey displayed rapid growth starting from 2014, 2017, and 2018, respectively. Collaborations between India and Saudi Arabia saw a remarkable escalation, with the number of collaborative publications increasing from 104 to 437 (approximately a 320% increment) over the four years from 2018 to 2021.

Complex network analysis was implemented on Country Collaboration Networks at four different temporal periods (2001 to 2005, 2006 to 2010, 2011 to 2015, and 2016 to 2021) to study the growth and diversification of international research collaborations of mathematics research in India over the two decades.

Table 3. Summary of the network properties of Country Collaboration Networks across different temporal periods. *k* represents the degree of nodes, while GC nodes denote the number of nodes in the giant component within each network. Note that the *k* (median), network density, and average clustering coefficients are representative properties of the giant component within each network.

Period	GC Nodes	*k* (Median)	Network Density	Average Clustering Coefficient
2001 - 2005	52	3	0.12	0.57
2006 - 2010	71	6	0.14	0.59
2011 - 2015	87	10	0.18	0.69
2016 - 2021	124	37	0.31	0.81

It can be observed from Table 3 that the properties of the giant components within the Country Collaboration Networks exhibit a consistent upward trend across successive periods. The increase in GC nodes reveals a rise in the number of countries engaging in research collaborations with India. The escalating trends in the median of *k* and network density reflect an increasing degree of heterogeneity in terms of countries in the collaborations. In general, this trend portrays a noticeable shift from exclusive collaborations with a limited set of countries towards a more diversified engagement with a wider array of countries. This evolving trend becomes apparent as shown by the concurrent increment in the average clustering coefficients.

Table 4. Top 5 countries ranked based on the eigenvector centrality in Country Collaboration Networks at various periods.

Period	Top 5 Countries	Eigenvector Score	Period	Top 5 Countries	Eigenvector Score
2001 - 2005	USA	1.00	2011 - 2015	USA	1.00
	Germany	0.73		Germany	0.97
	France	0.70		France	0.92
	Canada	0.61		England	0.89
	Italy	0.60		Italy	0.85
2006 - 2010	USA	1.00	2016 - 2021	USA	1.00
	England	0.91		China	0.98
	Germany	0.79		Italy	0.96
	France	0.75		Turkey	0.95
	Canada	0.72		England	0.95

The ranking of countries that collaborated with India in mathematics research based on the eigenvector centrality provides insight into the importance of various countries as mathematics research collaborators of India. In the Country Collaboration Networks, a country with high eigenvector centrality indicates that it is well-connected to other countries, which in turn are also significant collaborators in mathematics research with India. USA, England, Germany, France, and Italy remain the most important research collaborators of India in mathematics research at multiple periods. Notably, the USA maintains its leading status across all four periods, while the years 2016 to 2021 witnessed the rise of Turkey and China as the most important mathematics research collaborators of India. The variances in eigenvector centralities among the Top 5 countries demonstrate a declining trend across the periods (see Table 4). This pattern suggests that over time, the importance of various countries as mathematics research collaborators of India is progressively converging.

3.4 Institutional Collaboration

An analysis of the top Indian universities, engineering institutes, and research institutes shows that the Indian Institutes of Technology (IITs) is the most prolific contributor in mathematics research with 11118 publications, followed by the National Institutes of Technology (NITs) with 3497 publications. It must be noted that IITs consist of Indian institutions specializing in technology and engineering research, while NITs are a group of publicly funded Indian institutions specializing in engineering. Individual IITs such as IIT Madras (1728 publications), IIT Bombay (1536 publications), and IIT Kanpur (1519 publications) are amongst the top Indian institutes in mathematics research. Leading Indian research institutes, such as the Tata Institute of Fundamental Research (2617 publications) and the Indian Statistical Institute (2582 publications), which were active in the 1990s [6], continued to demonstrate substantial contributions to mathematics research throughout this study. Other notable Indian universities are the University of Delhi (1525 publications), Aligarh Muslim University (1516 publications), Institute of Mathematical Sciences India (1245 publications), Jadavpur University (1173 publications), and University of Calcutta (921 publications).

Table 5. Summary of the network properties of giant component in Institutional Collaboration Networks across different temporal periods

Period	Total Nodes	GC Nodes	k (Median)	Network Density	Average Clustering Coefficient
2001 - 2005	1381	1224	2	0.004	0.662
2006 - 2010	2835	2511	2	0.002	0.668
2011 - 2015	4195	3843	3	0.002	0.686
2016 - 2021	10044	9538	4	0.002	0.702

Table 5 depicts the growth of collaborative endeavour in mathematics research among academic institutions over different periods. The 2016 – 2021 period shows a major spike in activity with more than a doubling effect of mathematics research collaboration among Indian institutions, along with the most substantial growth in the size of giant component (GC Nodes) compared to prior periods. This observation parallels the growth of publications during the same time frame as seen in Figure 1.

The size of the giant component in the networks increases progressively over the periods, increasing from 31% of the total nodes during the 2001 – 2005 period to 47% during the 2016 – 2021 period, showing the gradual strengthening of collaborative effort among the institutions in mathematics research over the years.

The average clustering coefficients of the networks fall within the intermediate range. This phenomenon indicates that Indian institutions usually engage in mathematics research collaborations in cohesive clusters. However, low values in the median of k and network density suggest that such collaborations were small-scale research involving a small number of Indian institutions. This observation concurs with the analysis of the number of authors per publication, where most of the publications consist of less than 4 authors. From Table 6, it can be observed that publications with fewer than 4 authors make up roughly 80% of the total number of publications. This low average number of authors per publication is typical in mathematics research. Behrens and Luksch [28] reported that although the average number of authors per publication gradually rose over the years, it reached only 2 by the year 2008.

Table 6. Number of authors in a publication of mathematics research involving researchers from India institutions.

Number of Authors per Publication	Number of Publications	% of 57550
1	7380	12.82%
2	23222	40.35%
3	16080	27.94%
4	6540	11.36%
5	2438	4.24%
6	967	1.68%
7	394	0.68%
8	180	0.31%
9	122	0.21%
10	56	0.10%
More than 10	171	0.30%

Table 7. Summary of the network statistics of giant component in Institutional Collaboration Networks across different temporal periods.

Period	Top 5 Institutions	Eigenvector Centrality
2001 - 2005	Indian Institute of Technology (IIT, India)	1.00
	Indian Statistical Institute (ISI, India)	0.72
	Indian Institute of Science (IISC, India)	0.66
	Tata Institute of Fundamental Research (TIFR, India)	0.63
	Institute of Mathematical Sciences (IMS, India)	0.46
2006 - 2010	Indian Institute of Technology (IIT, India)	1.00
	Indian Institute of Science (IISC, India)	0.58
	Tata Institute of Fundamental Research (TIFR, India)	0.57
	Indian Statistical Institute (ISI, India)	0.43
	Institute of Mathematical Sciences (IMS, India)	0.40
2011 - 2015	University of Queensland (Australia)	1.00
	Indian Institute of Technology (IIT, India)	0.99
	University of Tennessee (USA)	0.99
	Johns Hopkins University (USA)	0.98
	Consiglio Nazionale delle Ricerche (Italy)	0.98
2016 - 2021	Technical University of Munich (Germany)	1.00
	Yale University (USA)	0.99
	University of Tokyo (Japan)	0.99
	University of Padua (Italy)	0.99
	University of Birmingham (UK)	0.99

Table 7 depicts the leading academic institutions that facilitate collaborations in mathematic research in India across various time frames. Indian academic institutions top the chart during the first two periods spanning from 2001 to 2010. However, the influence of international collaboration in the last two decades is prominent. We witnessed the emergence of international universities in the Top 5 such as the University of Queensland (Australia), University of Tennessee (USA), Johns Hopkins University (USA) and Consiglio Nazionale delle Ricerche (Italy) during the 2011 – 2015 period. In the subsequent period from 2016 to 2021, we see other players such as Technical University of Munich (Germany), Yale University (USA), University of Tokyo (Japan), University of Padua (Italy) and University of Birmingham (UK) come into the picture. A noteworthy observation is the eigenvector centralities of the Top 5 institutions during the last two periods. The eigenvector centralities exhibit equally high values, indicating a balanced influence among all the listed academic institutions in facilitating collaborative research endeavours in mathematics research in India.

4 Conclusion

The present work provided a different perspective on the status and development of mathematics research in India. General scientometric measures were used to describe the overall statistics of the research field, while complex network analysis was implemented to discern the dynamics in research collaborations. In terms of international collaboration, there is an increasing trend of research collaborations with other countries such as the USA, France, the UK and Italy. The emerging collaboration between Indian mathematicians with researchers from China and Turkey has been highlighted. In the context of complex network analysis, the growth in the size of the giant components in the networks signifies the increasing collaboration among Indian and non-Indian mathematicians from various academic institutions over several periods, especially during the 2016 – 2021 period. While it can be observed that IITs and NITs play a prominent role in facilitating research collaboration in mathematics research within India, other global universities such as the University of Queensland (Australia), University of Tennessee (USA), Johns Hopkins University (USA), Consiglio Nazionale delle Ricerche (Italy), Technical University of Munich (Germany), Yale University (USA), University of Tokyo (Japan), University of Padua (Italy) and University of Birmingham (UK) were also crucial in developing mathematics research in India. In concurrence with the study by Gangan [2] concerning science and technology research, we believe that mathematics research in India will see significant developments in the future. In terms of policy, Indian funding bodies should prioritize fostering international collaborations between Indian mathematicians and researchers from other research areas outside of India. This strategy can further enhance the contributions of Indian mathematicians in various scientific disciplines and technologies. For future work, it will be interesting to conduct a citation analysis on mathematics research in India to gain valuable insights into the contributions of India to the development of the mathematics research domain.

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