Journal of Scientometric Res. 2020; 9(3):253-267
http://www.jscires.org

Research Article

Evolving Trends of Indian Research Performance in Cryptography: A Bibliometric and Computational Investigation

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ABSTRACT
Cryptography is a crucial technique, involving protection of information and it's communication in a secure manner. This is a practice of storing transmitted data in a particular form that forbids an unauthorized person from accessing and processing the data. The application of modern cryptography in a combination of mathematical theories and various computer science techniques has become inevitable for securing digital information assets while defending the invasion of privacy in every sphere of modern society. This study aims to investigate the research performance of Indian cryptography research while identifying the most productive research institutes, authors, source titles and collaborating countries in terms of the number of publications and their citation impact. Alongside, the study also aims to identify the thematic evolution of Indian cryptography research during successive periods, using 'co-word cluster network analysis'. About 3767 (9.88 %) Indian publications of the total global publications of 38098 in the cryptography research were retrieved and analysed from Web of Science, within a time span of 1999–2018. This study identifies India's rank and most proficient organizations, authors, source titles and collaborating countries based on publication numbers and citation impact. Alongside, this study also quantified and visualized the distribution and impact of research fronts of Indian cryptography research at successive periods, through keywords overlapping map, strategic maps and thematic evolution map. The outcomes of this study will be useful to formulate future research policies that address further improvement of Indian cryptography research.

Keywords: Research performance, Cryptography, Thematic evolution, Scientometrics, Citation analysis.

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Received: 17-06-2020
Revised: 29-07-2020
Accepted: 14-10-2020
DOI: 10.5530/jscires.9.3.33

INTRODUCTION

A discipline devoted to the secrecy system is cryptology. Cryptography is the part of cryptology that deals with the design and implementation of the secrecy system. This secrecy system has become necessary for defence, banking, commerce, public administration, medical, education, web-based applications, ATMs, e-commerce, computer passwords, etc. Cryptography is an indispensable technique for protecting any information and communicating the same securely. This is a practice of storing transmitted data in a particular form that prevents any unauthorized access to it. In cryptography, the concealed information is usually termed as "plaintext" and the process of disguising the plaintext is defined as "encryption"; the encrypted plaintext is known as "ciphertext".[1] The process through a pair of algorithms that transfers a plain-text to cipher-text is encryption and the transformation of cipher-text to plain-text is decryption.[2]

Modern cryptography is mainly based on mathematical theories that are being applied through various computer science techniques. The field of modern cryptography not only incorporates secrecy in communication but also the other mechanisms viz., message authentication, digital signatures, protocols for exchanging secret keys, authentication protocols, electronic auctions and elections and digital cash.[3] The application of cryptographic techniques has become inevitable to safeguard digital information assets and to defend the invasion of privacy in every sphere of modern society.[4] Comprehensively, modern cryptography can be defined as the study of mathematical techniques for securing digital information, systems and distributed computations against adversarial attacks.[5]

Presently, blockchain technology is conquering accelerated importance as a new horizon of research area since it was conceptualized in 2008 which adopts cryptography as an integral component. It uses two types of cryptographic algorithms, viz., asymmetric-key algorithms and hash

functions. Blockchain is a decentralized transaction and data management technology, initially developed for the Bitcoin cryptocurrency.[6] It provides security, anonymity and data integrity without any third-party organization in control of the transactions. The potential benefits of the blockchain include economic, political, humanitarian, social and scientific domains to address real-world problems.[7]

Scientometric analysis of cryptography research output apparently measured the academic productivity and distribution of research diversity by four major countries namely China, USA, Taiwan and Japan from the Web of Science (WoS) database.[8] The intellectual development of cryptographic research has been quantified by analysing the publication growth, authorship pattern, collaboration trends and predominant areas of research in cryptology published in the Journal of Cryptology.[9] Another study has also identified productive-authors, potential-collaborators, predominant-institutions, prolific-countries and prevalent topics of cryptology research.[10] One bibliometric study followed by another scientometric study, subsequently identified the global research output of the authorship collaboration pattern in cryptography research from 1976 to 2015 from the Scopus database.[11] Recently, one study identified the research performance and thematic evolution of China in quantum cryptography.[12]

Scope and Objectives

So far no one has evaluated the Indian research performance as a whole, nor analysed the comparative thematic evolving trend with the global context in the domain of cryptography research. The present study is aimed to analyse the performance and thematic evolution of Indian cryptography research at successive periods by adopting various bibliometric and scientometric methods. This study also helps in identifying the most productive organizations, authors, source titles, research areas and to understand the impact of research collaboration in this field. Present investigation will disseminate valuable information about Indian cryptography research performance in terms of strength and lacuna as compared to the global scenario. Alongside, the identification of the most prolific organizations, authors and collaborating countries will indicate the key actors in this field for research cooperation. Core source title's information will instigate new research design and research communication. The thematic evolution study will be helpful in identifying significant and nonsignificant subdomains at successive periods facilitating researchers to design their future research work accordingly.

Advancements in Global and Indian cryptography research

Various studies identified the application of cryptography in network security,[13] data loss prevention,[14] protection against personal data breach.[15] Cryptographic techniques are also considered as a possible solution for security through smart cards, PINs, password authentication and biometric-based keys,[16] protection of application-based wireless networks with the help of Mobile Application Security System (MASS)[17] and application of quantum encryption to enable ultra-secure communications and near-perfect data security.[18] As an emerging field of research, the applications of blockchain technology are growing at a higher pace in different fields viz. Internet of Things (IoT),[19] protection of personal data,[20] protection of healthcare data,[21,22] security of energy trading,[23] future prospects of Bitcoin,[24] and so on.

Information security has been one of the most important concerns for countries throughout the globe during the last two decades. India has also made immense progress towards information security over the last decade.[25] Realizing the magnitude of its significance, Government of India adopted the "National Cyber Security Policy -2013" with the mission "to protect information and information infrastructure in cyberspace, build capabilities to prevent and respond to cyber threats, reduce vulnerabilities and minimize damage from cyber incidents through a combination of institutional structures, people, processes, technology and cooperation".

Several publications of Indian authors have received higher number of citations as important research work. Nandi *et al*.[26] applied Cellular Automata theory for a class of block ciphers and stream ciphers towards better security against different types of attacks. Some studies constructed different cryptographically significant Boolean functions for better algebraic immunity.[27,28] Different image encryption techniques based on chaotic logistic maps have been applied for secure image transfer,[29] to manage the trade-offs between the security and speed and hence suitable for the real-time secure image and video communication applications[30] and faster synchronization of different fractional-order chaotic systems using active control.[31] Islam and Biswas[32] proposed the elliptic curve cryptosystem (ECC) for a more efficient and secure ID-based remote mutual authentication with key agreement schemes for mobile devices. A framework comprising of different techniques and specialized procedures is proposed to ensure data security in cloud computing.[33] Another study proposed a new secure multi-server authentication protocol using a biometric-based smart card and ECC with more security functionalities.[34]

It has been observed from the WoS database that Indian authors contributed about 368 publications on blockchain technology to date (retrieved on 19.08.2020). Some of the highly cited studies revealed various important applications of blockchain technology. A survey study has addressed the existing vulnerabilities in Bitcoin where from the blockchain technology pioneered.[35] A couple of studies identified the

feasible application of blockchains with the internet of things (IoT) in providing security management and analysis of healthcare big data[36,37] and in enhancing the security level in IoT.[38] Other applications of blockchain are involved in the supply chain in India,[39] a framework for the automotive industry in the smart city[40] and data storage for wireless sensor networks.[41]

Developments in Bibliometrics and Scientometrics

Bibliometrics is a set of methods to quantitatively analyse scientific and technological literature and hence can be applied and extended to all types of research work, thus making it a truly interdisciplinary approach.[42] These techniques implement statistical and mathematical tools to measure the data that literally quantifies a researcher's contribution in the development of science and technology.[43] While figuring out the quality of published work, evaluating research trends, performance of countries, research institutes, keywords and authors, bibliometric network analysis has been used quite frequently.[44-49] The common network analysis included co-word analysis[50,51] and co-citation analysis.[52,53] Nalimov and Mulchenko[54] defined the term "scientometrics" as the quantitative study of various kinds of intelligence processes in the development of science. The scientometric method measures the evolution of a scientific domain, the impact of research publications and the trends of scientific knowledge production, mainly from publication output, subject category,[55] journal, author, country,[56] research institute[57] and keyword frequencies.[58]

MATERIALS AND METHODS

Publication data collection

The publication data were collected using a specific search string from WoS Core Collection, previously owned by Thomson Reuters and presently owned by Clarivate Analytics. These databases cover a wide range of research fields and are the most common data sources for bibliometric-related studies. The search string (TS=cryptograph*) was used to retrieve publication data selecting the "Advance Search" option of the database. About 38098 global publications were recorded during the last 20 years (1999-2018). During the same period about 3767 Indian publications were recorded and used for analysis of various parameters.

Bibliometric parameter analysis

Publication data of the top 10 countries were retrieved from the database for a comparative analysis. All bibliographic records related to the Indian publications considered for the present study, were downloaded for further analysis using the "Analyze Results" option of WoS. Publication data, organization's names, author's names, collaborating country's names, WoS categories and source titles were isolated separately to examine the collected data for assurance of their identity. The data were further analysed in Microsoft Excel and R. The 20 years' span of study was further divided into 4 periods of five years each to visualize the evolving trends of research in this field.

Citation and *h*-index analysis

Citation data of the total publications were obtained by selecting the "Create Citation Report" key. The citation reports of individual countries, institutions, authors, source titles and research collaborations were created and downloaded for further analysis. Graphs were plotted to show the period wise trends of *h*-indices, citations and the number of publications for quality analysis. *h*-index data for countries, institutions, authors, and source titles were also analyzed in WoS. The mean total citation per year (i.e. citation received per year) was calculated at successive periods to normalize the citation data of Indian publications and presented graphically.

Research collaboration analysis

The publication data of Indian collaborative research in cryptography were retrieved separately by selecting all countries taking part in the Indian publications except India and then refined. The publication data from India without any research collaboration were also retrieved separately after excluding all the other countries in the Indian publications, while counting India, per se. Accordingly, a comparative study among Indian international collaborative publications and Indian publications without any international collaboration was performed by analysing the number of publications, total citations, average citation per item and *h*-index, calculated five-year impact factor and publication distributions among different citation categories to understand the impact of Indian collaborative research. Besides this, a comparative analysis was also performed among the top 15 countries, collaborating with Indian researchers by analysing the number of publications, average citation per item and *h*-index and represented graphically.

Thematic evolution analysis

The thematic evolution of Indian and global cryptography research was studied using Science Mapping Analysis Software Tool (SciMAT)[59] which provides a temporal or longitudinal analysis. As mentioned before, the total 20 years' time-span was further divided into four periods of five years each to understand the thematic evolution of the cryptography research front of India at successive periods. Themes were operationally defined and labeled based on keyword clusters derived from co-word analyses. Cluster's information of strategic maps was represented in tabular form by giving their centrality, density, document counts, document *h*-index and document

citations for different periods to understand the thematic evolution. The cluster network processing parameters were applied as follows: 1) the minimum document frequencies were set at successive periods as 1, 2, 3, 4 for Indian publications and 3, 4, 5, 6 for global publications; 2) co-occurrence was selected as the matrix preference; 3) the minimum co-occurrence frequencies were set at successive periods as 1, 2, 3 and 4 for Indian publications and 2, 3, 4, 5 for global publications; 4) the equivalence index was chosen as the normalization measure; 5) the simple centres clustering algorithm[60] was used with a maximum network size of 15 and a minimum network size of 2 for Indian publications and 4 for global publications; 6) both the core and the secondary mappers were selected; 7) the *h*-index and the sum citation evaluative measures were selected for node display; and 8) Jaccard's index[61] and the inclusion index[62] were chosen as measures for longitudinal and overlap mapping. The comparative thematic evolutions of Indian and global cryptography research are shown through an overlapping map in addition to a thematic evolution map.

RESULTS

India's rank in global publications

A total of 38098 global publications on cryptography was observed during 20 years (1999-2018) from the WoS Core Collection database. A total of 130 countries were found to have made contributions in cryptography research. The top 10 and top 20 countries were found to have contributed in 65.37 % and 81.87% of the total global publications, respectively. From the publication data demonstrated in Figure 1 shows China's remarkable contribution of 20.09% share of the total publications, which is the highest among all, followed by USA 18.19%.

India stood 3rd in position, by contributing in about 3767 publications (9.88%) mainly in the form of proceeding papers and articles. Figure 1 represents the number of publications, average citation per publication (ACPP) and *h*-indices, which reflects productivity and quality of publication as well as the citation impact of the top 10 countries on cryptography research. England has registered with the highest ACPP 24.42 with 1593 publications whereas USA registered the highest *h*-index of 177 with 6933 publications. India held the lowest position in the rank list of ACPP (4.05 ACPP) along with the lowest *h*-index (48) among the global top 10 countries.

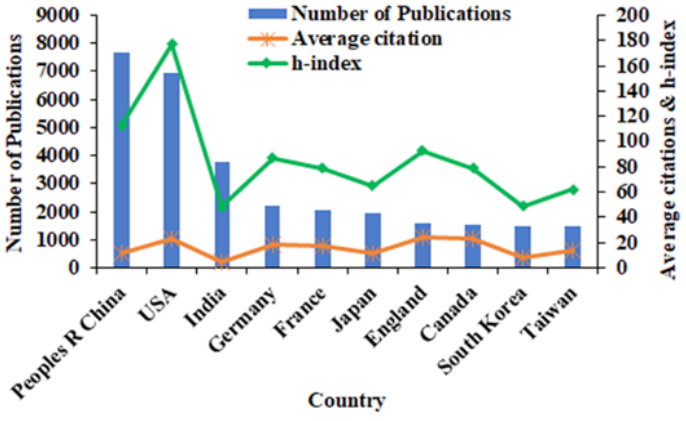


Figure 1: Top 10 country's number of publications, average citations per publications and *h*-index.

Period-wise growth of bibliometric parameters

Figure 2 exhibits the period-wise growth of the number of publications (Figure 2A), organisations (Figure 2B), authors (Figure 2C), collaborating countries (Figure 2D), WoS categories (Figure 2E) and source titles (Figure 2F). Bibliometric parameters were found to have increased from the first period (1999-2003) through the last period (2014-2018). It showed the growth of Publications from 49 to 2733, no. of organisations involved from 54 to 1593, no. of authors from 87 to 4622, no. of collaborating countries from 13 to 56, inclusion of categories in WoS from 15 to 67 and no. of source titles from 28 to 905 with a compound period-wise growth rate (CPGR) of 282.07%, 208.99%, 275.93%, 62.71%, 64.69% and 218.54%, respectively. The number of publications had increased during the last period (2014-2018) by more than three times, as compared to that of the preceding period (2009-2013).

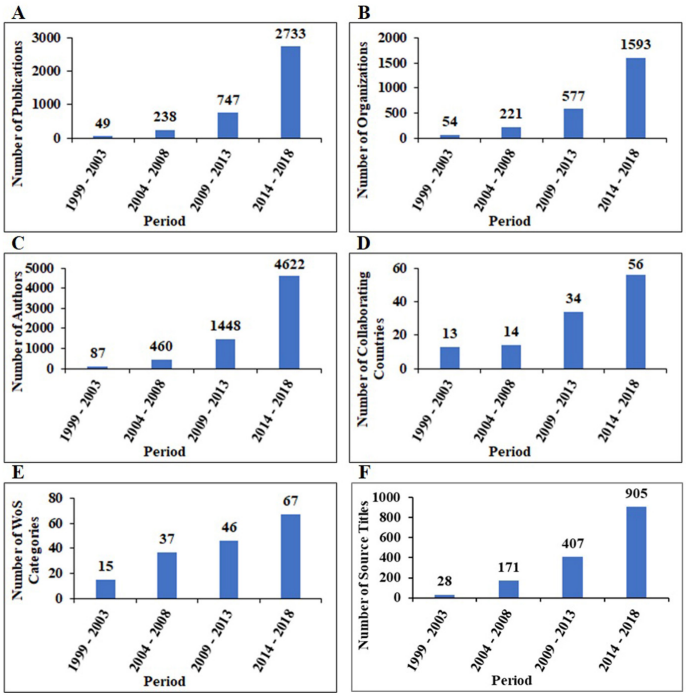


Figure 2: Period-wise growth of different bibliometric parameters: A. number of publications, B. number of organisations, C. number of authors, D. number of collaborating countries, E. number of WoS categories and F. number of source titles.

Period-wise citation impact

Figure 3 shows the *h*-index and mean total citations received per year at successive periods. *h*-index depends on the citation of the papers, which reflects productivity and quality of the publication. Figure 3 exhibited that *h*-index did gradually improve throughout the period and the mean total citation per year decreased from 0.97 during the initial period (1999-2003) to 0.72 during the 3rd period (2009-2013) then had increased to 0.82 during the last period (2014-2018). Figure 4 exhibits the distribution of publication % in different citation categories during different periods viz., above 500, 201 to 500, 101 to 200, 51 to 100, 21 to 50, 11 to 20, 6 to 10, 1 to 5 and 0 (no citation). It has been observed that the % of publication was higher in the no citation category followed by the '1 to 5 citation(s)' category throughout the periods and in the higher citation category, the % of publication was lower. Only one publication scored above 500 citations throughout the periods i.e. during the 2004-2008 period. Uniform publication distributions (14 to 16%) have been observed among the citation categories of 1-5, 6-10, 11-20 and 21-50 during the 1999-2003 period. About 51.88% of the total publications had no citations during 2014-2018 as compared to the initial period 1999-2003 (28.57%).

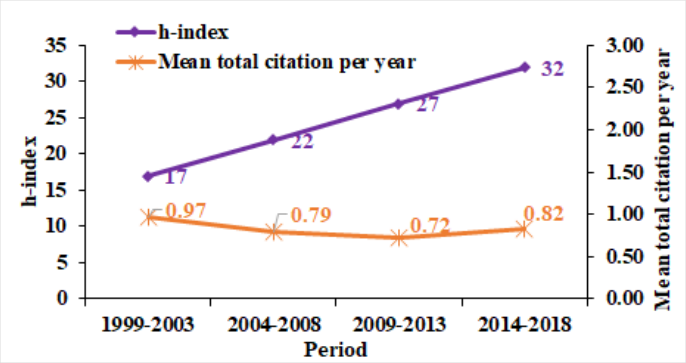
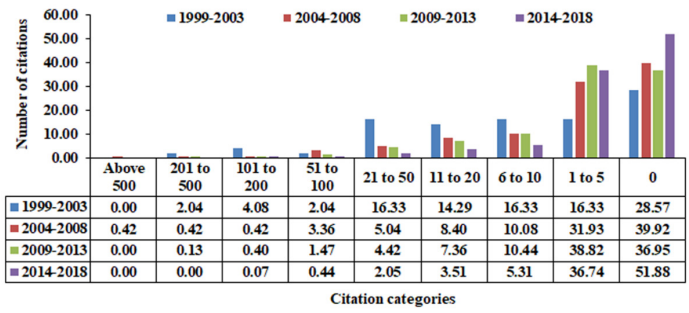


Figure 3: Period-wise mean total citation per year (normalised citation) and h-index.



	Above 500	201 to 500	101 to 200	51 to 100	21 to 50	11 to 20	6 to 10	1 to 5	0
1999-2003	0.00	2.04	4.08	2.04	16.33	14.29	16.33	16.33	28.57
2004-2008	0.42	0.42	0.42	3.36	5.04	8.40	10.08	31.93	39.92
2009-2013	0.00	0.13	0.40	1.47	4.42	7.36	10.44	38.82	36.95
2014-2018	0.00	0.00	0.07	0.44	2.05	3.51	5.31	36.74	51.88

Figure 4: Publication % in different citation categories during different periods.

Contribution by top 20 Organizations

Figure 5 represents the number of publications, total citations and *h*-indices of the top 20 Indian organizations towards the cryptography research. Top 20 Indian organizations had contributed a total of 1205 publications, with a publication share of about 32% of total Indian publications from 1999 to 2018. Only 6 institutes recorded a higher publication output than the group average of 60.25. Indian Institute of Technology, Kharagpur held the top rank after contributing 158 publications, followed by the Indian Statistical Institute (118), Anna University (100) and Thapar Institute of Engineering Technology (81).

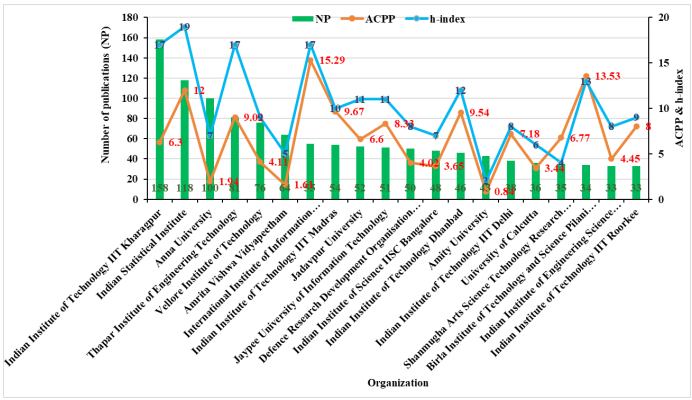


Figure 5: Number of publications by top 20 organizations and their average citation and h-index.

The publications of the top 20 organizations have received 54% citations among the total Indian publications. The group average of 'average citation per publication (ACPP)' of the top 20 organization is 6.81 which is quite higher than the ACPP (4.02) of the total Indian publications. Nine organizations have scored higher ACPP than the group average. International Institute of Information Technology, Hyderabad has achieved the highest rank with 15.29 ACPP followed by Birla Institute of Technology and Science (BITS), Pilani with a 13.53 ACPP and Indian Statistical Institute with an ACPP of 12. Eight organizations have scored higher *h*-indices than the group's average *h*-index of 10. The Indian Statistical Institute attains the top rank having the highest *h*-index of 19 followed by the Indian Institute of Technology IIT Kharagpur (17), Thapar Institute of Engineering Technology (17) and International Institute of Information Technology Hyderabad (17).

Contribution by top 20 authors

Figure 6 represents the number of publications, ACPP and *h*-indices of the top 20 Indian authors towards the cryptography research. Top 20 Indian authors had contributed a total of 621 publications yielding a publication share of about 16.48% of total Indian publications during the period 1999 to 2018. Mukhopadhyay D. has contributed the highest number

of papers (63) with 1.67% share of publications, followed by Kumar A. (47 papers with 1.24% share), Kumar N. (42 papers with 1.11% share), Maitra S. (40 papers with 1.06% share). Only 8 authors have a higher publication contribution than the group average of 31.05. The publications of the top 20 authors have received 37.77% citations of the total Indian publications. The group average of ACPP of the top 20 most productive authors is 9.5 which is more than two times higher than the ACPP (4.02) of the total Indian publications. Half of the authors have registered higher ACPP than the group average ACPP of 9.5. Maitra S. (ACPP 24) leads the list followed by Islam S.K.H. (ACPP 20), Kumari S. (ACPP 20), Pathak A. (ACPP 16) and Das A.K. (ACPP 15). Like that of the ACPP half of the authors have scored higher *h*-indices than the group's average *h*-index of 8.6. Maitra S. also leads the list with an *h*-index of 16, followed by Das A.K. (14), Islam S.K.H. (14), Kumar N. (12), Pathak A. and Kumari S. (11).

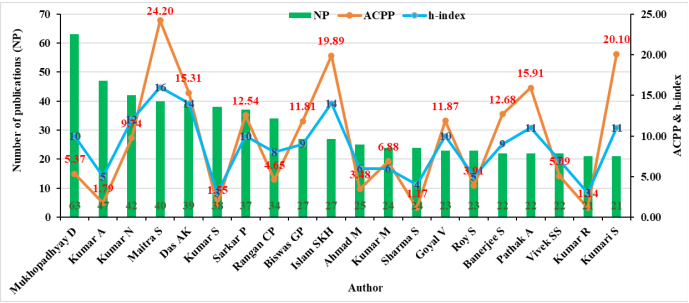


Figure 6: Number of publications by top 20 authors and their average citation and h-index.

Contribution by top 20 source titles

Globally, cryptography research has been published under 10345 source titles, out of which the top 20 source titles appeared in 29.49 % of total global publications. Authors from India have contributed in 1579 source titles out of which the top 20 source titles were found in 18.56% of total Indian publications (Figure 7). India has contributed at a higher proportion in some source titles namely: Communications in Computer and Information Science (163) and Advances in Intelligent Systems and Computing (123) and in the rest of the source titles India has contributed at a very lower proportion (Figure 7).

Figure 8 represents the number of publications (NP), ACPP and *h*-indices of top 20 source titles based on NP of Indian publications on cryptography research. Top 20 source titles of Indian publications have contributed in a total of 1014 publications with 26.91% share of total Indian publications from 1999 to 2018. Lecture Notes in Computer Science has registered the highest number of publications (NP 202 with 5.36% share) followed by Communications in Computer and Information Science (NP 162 with 4.30% share), Advances in Intelligent Systems and Computing (NP 126 with 3.34% share), Procedia Computer Science (NP 90 with 2.39% share), Multimedia Tools and Applications (NP 40 with 1.06% share), Wireless Personal Communications (NP 39 with 1.03% share) and other source titles with less than 1% publication share. Only 4 source titles have a higher publication contribution than the group average of 50.7. The publications of the top 20 source titles have received 33.53% citations of the total Indian publications. The group average of ACPP of the top 20 most productive source titles is 4.65 which is slightly higher than the ACPP (4.02) of the total Indian publications. Half of the source titles have registered higher ACPP than the group average ACPP of 4.65. Physical Review A (ACPP 13.32) leads the list followed by Quantum Information Processing (ACPP 12.83) and Lecture Notes in Computer Science (ACPP 10.37). It has also been observed that five source titles (international conference proceedings) scored ACPP of less than 1. Like that of the ACPP half of the source titles have scored higher *h*-indices than the group's average *h*-index of 6.35. Lecture Notes in Computer Science leads the list with an *h*-index of 20 followed by Procedia Computer Science (12), Quantum Information Processing (11) and other source titles have an *h*-index below 9.

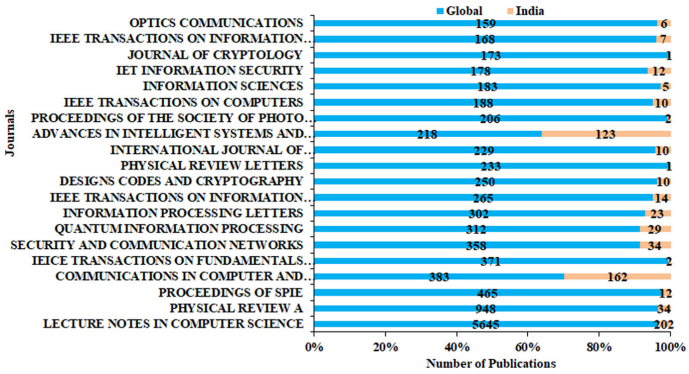


Figure 7: Top 20 source titles of total global publication and contribution of India in the top source titles.

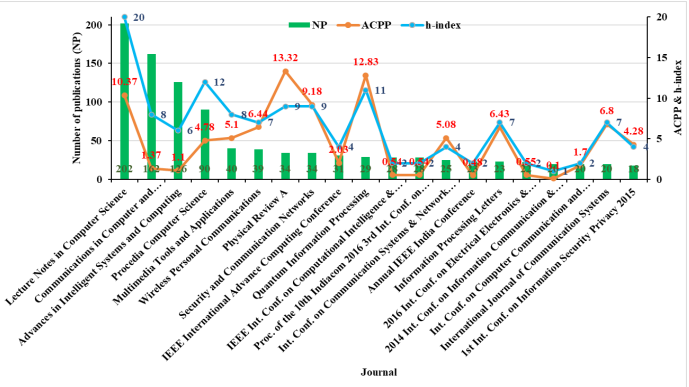


Figure 8: Number of publications by top 20 source titles and their average citation and h-index.

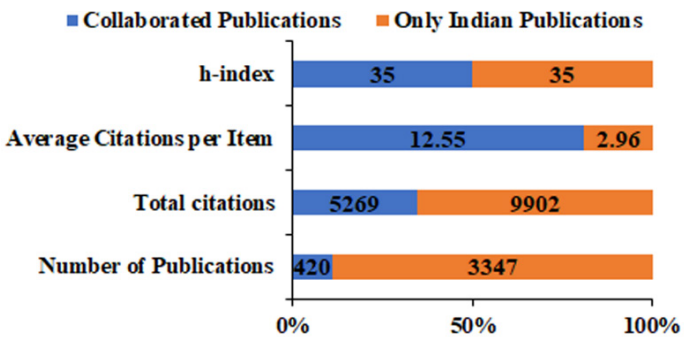


Figure 9: Number of publications, h-index, total citation, average citation per publication of the collaborated publications and only Indian publications.

Research collaboration

India has published 420 multinational or collaborative publications with 64 countries on cryptography research which is 11.15% of total Indian publications during 1999–2018. Figure 9 represents the number of publications, total citations, average citation per publications and *h*-indices of collaborated as well as non-collaborative Indian publications. The collaborated Indian publications have received 5269 total citations with an ACPP of 12.55 while Indian publications sans collaboration (3347) had received 9902 total citations with an ACPP of 2.96 which is more than 4 times lower than the ACPP of collaborated Indian publications. The *h*-index value is similar for both collaborative publications and only Indian publications.

Period-wise calculated 5-year impact factor

Five-year impact factors of different periods were also calculated from citation data for comparative quality analyses among collaborated Indian publications and Indian publications sans collaboration. Five-year impact factor of total Indian publications has decreased from 1.27 during the initial period (1999–2003) to 0.88 during 2014–2018 (Figure 10). Five-year impact factor of Indian publications sans collaboration also dropped down from 1.15 during initial period (1999–2003) to 0.60 during 2014–2018 which is a lower publication from total Indian publication. In contrary to the previous two categories the five-year impact factor of collaborated Indian publications has increased from 1.70 during the initial period (1999–2003) to 3.34 through the last period (2014–2018).

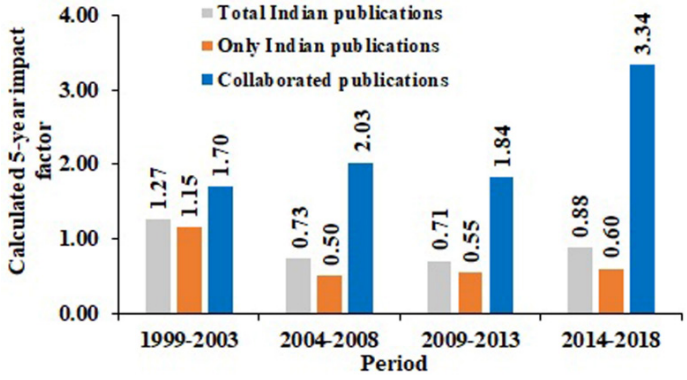


Figure 10: Period-wise calculated 5-year impact factor of the publications of the total Indian publication, only Indian publication and collaborated publication.

Figure 11 represents the publication distributions of Indian publications on cryptography with and without collaborations, among different citation categories viz., above 500, 201 to 500, 101 to 200, 51 to 100, 21 to 50, 11 to 20, 6 to 10, 1 to 5 and 0 or no citation. The present study shows that more than 50 % of publications done solely by Indian authors did not receive any citation whereas, in case of publications coming out of collaboration, that number was only 21.19%. Publications coming solely from Indian authors, scored a higher percentage of publication distribution (36.99%) in the lower citation category (1 to 5) as compared to that of the Indian publications coming out of collaboration (33.33%). On the contrary, in case of higher citation categories, an opposite trend was evident. It has been observed that in the higher citation categories % of publications did decline gradually in case of Indian publications sans collaboration (06 to 10 citations = 6.01% publication, 11 to 20 citations =3.47% publication, 21 to 50 citations =1.67% publication, 51 to 100 citations =0.45% publication, 101 to 200 citations = 0.15% publication, 201 to 500 citations = 0.03% publication). Similar results were also evident in the case of collaborated Indian publications but the % of publications in 06 to 10, 11 to 20 and 21 to 50 citation categories were 12.86, 14.76 and 12.62, respectively.

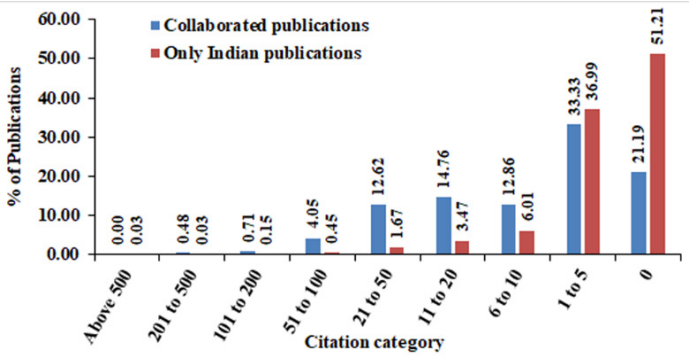


Figure 11: Publication % in different citation categories for collaborated publications and only Indian publications.

Contribution and citation impact of leading collaborative countries

Among the 64 collaborating countries, the top 15 have contributed in more than 72% (normalised) of total Indian collaborated publications. India has published the maximum collaborative research publications with the USA (135) followed by China (35), Canada (32) and England (31)

(Figure 12). France has registered highest ACPP of 27.6 with 20 publication followed by China (ACPP 16.41 with 35 publications), Saudi Arabia (ACPP 14.37 with 19 publications) and USA (ACPP 14.01 with 135 publications). USA also leads the *h*-index list with 21 *h*-index, followed by China (18), South Korea (13), Canada and England (11).

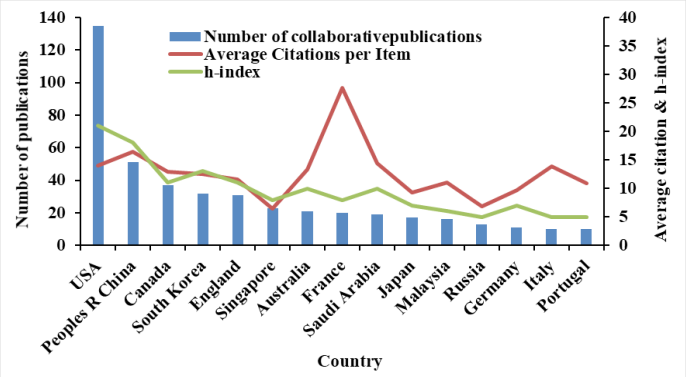


Figure 12: Number of collaborated publications, average citation per publication (ACPP) and *h*-index of top 15 collaborating countries.

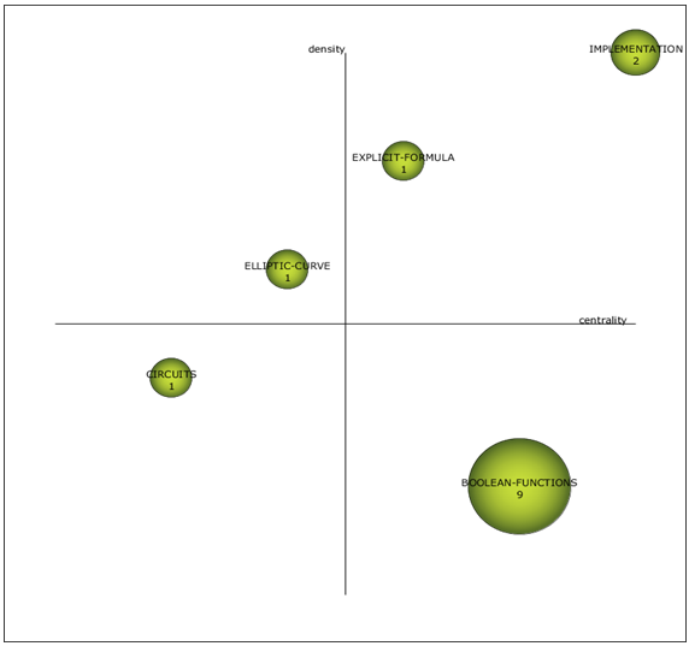


Figure 13: Strategic diagram of themes during 1999-2003.

Quantitative and qualitative development of themes at successive periods

Thematic evolution was represented through strategic diagrams at successive periods. Themes were plotted as circles denoting different theme clusters according to centrality and density in strategic diagrams. The size of the circle is proportional to the number of documents and referred to as document frequency (DF) in which its linked or related keywords are present. Cobo *et al.*[60] has described that the strategic diagrams are divided into four quadrants and it can be interpreted as follows: the top-right quadrant represents "motor themes", the top-left quadrant represents "highly developed and isolated themes", the bottom-left quadrant represents "emerging or declining themes", the bottom-right quadrant represents "basic and transversal themes".

During the initial period (1999-2003) a total of only 30 keywords were observed among the total 49 publications. The initial period has registered five themes with very fewer DF. The theme "BOOLEAN-FUNCTIONS" has the maximum DF of 9 followed by "IMPLEMENTATION" with a DF of 2 (Figure 13, Table 1). As per document citations, the "BOOLEAN-FUNCTIONS" theme has scored a higher citation of 219 as the most important and relevant theme. Although, the theme "IMPLEMENTATION" has positioned itself in the top-right quadrant with the highest centrality and density value which indicates that the theme is well connected with other keywords vis-à-vis themes.

During 2004-2008 total keywords have increased to 124 with a growth rate of 313.33% among the total 238 publications (increased by 385.71%). The number of themes did also increase to 10 during this period with comparatively more DF. During this period "STREAM-CIPHER" was found to be the most active theme having a DF of 17 followed by "CRYPTOSYSTEMS" with a DF of 9 (Figure 14, Table 2). The theme "STREAM-CIPHER" received maximum document citations (423) followed by "CRYPTOSYSTEMS" (86). The theme "STREAM-CIPHER" was positioned in the top-right quadrant with the highest centrality value indicating itself as the most important and well-connected theme with other keywords vis-à-vis themes. The theme "CRYPTOSYSTEMS" appeared in the bottom-right quadrant as basic and transversal themes. The theme "EXPANDER-

Table 1: Quantitative and qualitative performance measures of themes during 1999–2003.

Theme	Centrality	Density	Document Frequency	Document *h*-index	Document Citations
BOOLEAN-FUNCTIONS	5.75	38.84	9	7	219
IMPLEMENTATION	7.5	53.12	2	1	6
CIRCUITS	0	50	1	1	18
ELLIPTIC-CURVE	0	50	1	1	16
EXPLICIT-FORMULA	0	50	1	1	8

GRAPHS" was positioned in the top-left quadrant showing the highest density, having no centrality and document citations; thus making it seem like an isolated theme.

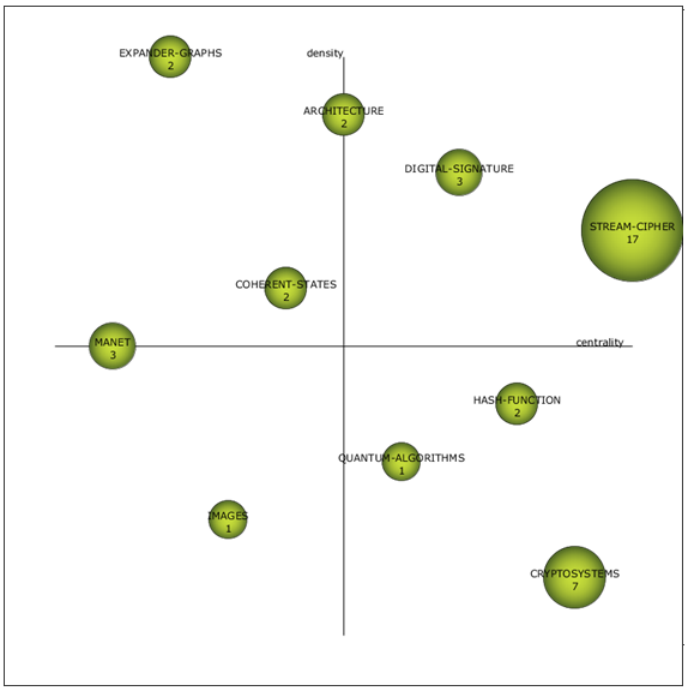


Figure 14: Strategic diagram of themes during 2004-2008.

During the third period, total keywords were found to have increased to 239 with a growth rate of 92.74% among the entire 747 publications (increased by 213.86%). Total number of themes remained at 10 during this period with more or less uniformly distributed DF. During this period "BIOMETRICS" was the most active theme having a DF of 10 followed by "MAPS" with a DF of 10 (Figure 15, Table 3). The theme "SCHEME" has received maximum document citation (221) followed by "MAPS" with a document citation of 73, "BENT-FUNCTIONS", "BIOMETRICS" with a document citation of 55 and "BIOMETRICS" with a document citation of 36. The theme "BIOMETRICS" was positioned in the top-right quadrant with the highest centrality value (4.35) indicating its highest importance and the fact that it was well-connected with other keywords vis-à-vis themes followed by "AUTHENTICATION-PROTOCOL" (2.92) and "SCHEME" (2.02). The theme "POWER-ATTACK" was positioned in the top-left quadrant with no centrality, thereby assigning it as an isolated theme. The themes "KEY-MANAGEMENT", "ACCESS-CONTROL" and "DES" were found to come under emerging focus, as they were positioned in the bottom-left quadrant.

During the last study period (2014-2018), the number of themes were found to have increased to 14, with higher DF for each theme indicating higher diversity and development

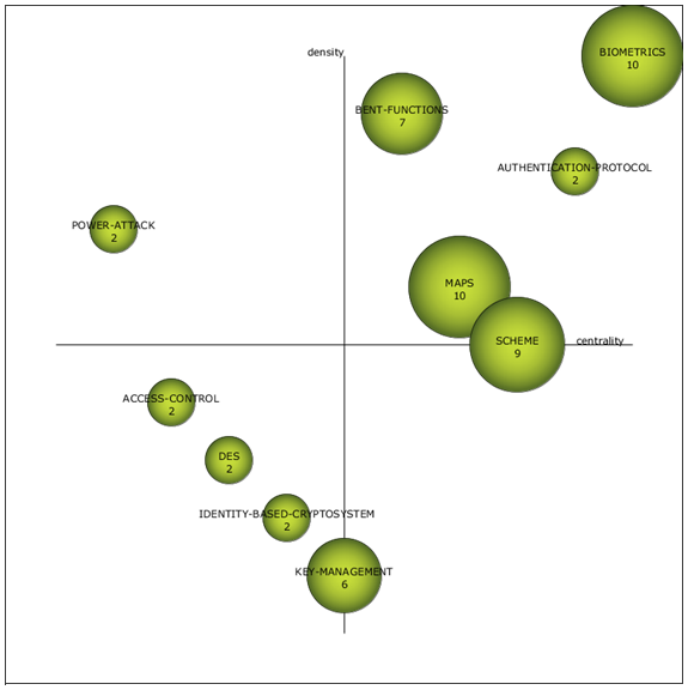


Figure 15: Strategic diagram of themes during 2009-2013.

Table 2: Quantitative and qualitative performance measures of themes during 2004–2008.

Theme	Centrality	Density	Document Frequency	Document *h*-index	Document Citations
STREAM-CIPHER	20.48	26.15	17	7	423
CRYPTOSYSTEMS	15.52	7.44	7	4	86
HASH-FUNCTION	6.62	13.54	2	1	10
DIGITAL-SIGNATURE	4.93	28.27	3	2	4
MANET	0	15.56	3	1	9
EXPANDER-GRAPHS	0	50	2	0	0
ARCHITECTURE	1.67	33.33	2	2	4
COHERENT-STATES	1.11	22.22	2	1	3
IMAGES	0	12.5	1	1	10
QUANTUM-ALGORITHMS	4.12	12.5	1	1	3

Table 3: Quantitative and qualitative performance measures of themes during 2009–2013.

Theme	Centrality	Density	Document Frequency	Document *h*-index	Document Citations
BIOMETRICS	4.35	28.18	10	4	36
SCHEME	2.02	6.55	9	4	221
MAPS	1.73	6.83	10	5	73
BENT-FUNCTIONS	1.53	18.38	7	4	55
KEY-MANAGEMENT	0.83	1.69	6	1	6
AUTHENTICATION-PROTOCOL	2.92	16.67	2	2	10
POWER-ATTACK	0	8.33	2	2	30
ACCESS-CONTROL	0	4.17	2	1	12
DES	0	3.57	2	2	15
IDENTITY-BASED-CRYPTOSYSTEM	0	3.33	2	2	30

of Indian cryptography research (Figure 16, Table 4). During this period, Indian cryptography research activity increased remarkably; the number of publications increased to 2733 while the number of keywords increased to 385, with a growth rate of 265.86% and 61.09%, respectively, even though, the growth rate of keywords was lower than the previous period. The theme "SCHEME" appeared at the top-right quadrant as the most central motor and recent theme with a DF of 87 along with the maximum citations record of 724. The theme "WIRELESS-SENSOR-NETWORKS" appeared as a basic transverse theme as positioned in the bottom-right quadrant with a DF of 64 and received 342 citations as an important theme.

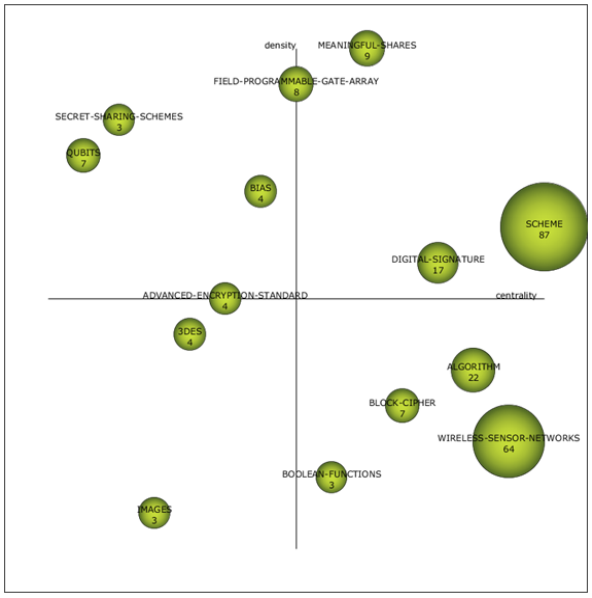


Figure 16: Strategic diagram of themes during 2014-2018.

Quantitative evolution of keywords

The quantitative evolution and exchange of keywords from the previous period to the next period are represented in Figure 17 and Figure 18 for total Indian and global

Table 4: Quantitative and qualitative performance measures of themes during 2014–2018.

Theme	Centrality	Density	Document Frequency	Document *h*-index	Document Citations
SCHEME	10.44	4.01	87	15	724
WIRELESS-SENSOR-NETWORKS	8.29	1.09	64	8	342
ALGORITHM	3.59	2.63	22	3	71
DIGITAL-SIGNATURE	2.29	3.78	17	3	32
MEANINGFUL-SHARES	0.79	16.02	9	3	17
FIELD-PROGRAMMABLE-GATE-ARRAY	0.48	12.22	8	1	16
QUBITS	0	5.02	7	4	32
SECRET-SHARING-SCHEMES	0	8.04	3	1	19
BIAS	0.14	4.3	4	2	28
ADVANCED-ENCRYPTION-STANDARD	0.13	3.14	4	1	6
3DES	0.06	2.78	4	2	32
BLOCK-CIPHER	1.17	2.51	7	4	33
BOOLEAN-FUNCTIONS	0.64	1.02	3	1	1
IMAGES	0	0.69	3	1	4

publications, respectively. Each circle contains the number of keywords during that period which is indicated below the circle. The arrow containing the number of keywords coming towards the circle indicates newly arisen keywords. On the other hand, the arrow going outside indicates the number of keywords that are not used at successive period. The arrow pointing from the previous to successive period represents the number of keywords exchanged (integer value) and the fraction of overlap (i.e., Similarity Index) in parentheses.[60]

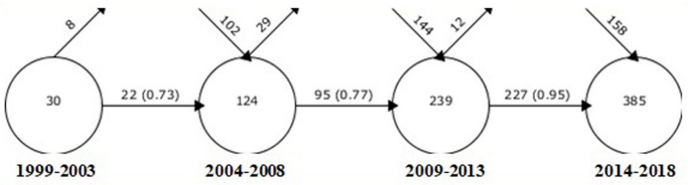


Figure 17: Overlapping map of keyword's quantitative perspective during successive periods of Indian Publications.

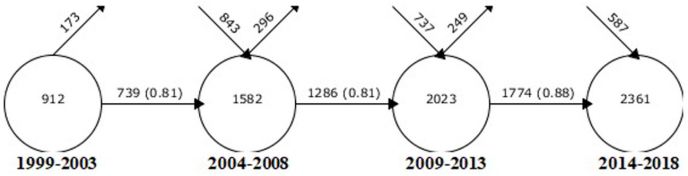


Figure 18: Overlapping map of keyword's quantitative perspective during successive periods of global publications.

The higher value of the similarity index indicates the core themes of Indian cryptography research remain more or less continuous, whereas, the quantity of newly evolved keywords indicates the advancement of the core theme in different sub-themes. Number of keywords did increase from 30 during the initial period to 385 during the latest period with a CPGR of 134.12%. On the other hand, the number of keywords of global cryptography research had increased from 912 during the initial period to 2361 during the last study period, with a CPGR of 37.30% which was lower than the Indian CPGR. Indian cryptography research has incorporated a higher proportion of new keywords at successive periods (82.25% during 2004-2008, 60.25% during 2009-2013, 41.03% during 2014-2018) as compared to the global proportions (53.28% during 2004-2008, 36.43% during 2009-2013, 24.84%. during 2014-2018).

Thematic evolution

Figure 19 and Figure 20 represent the thematic evolution of Indian and global cryptography research, respectively. Different themes were plotted in the columns for each period indicated below their designated column. The size of the node indicating theme cluster, is proportional to the number of published documents associated with each theme cluster. Themes having a relationship between periods are connected by links. The thickness of the link is proportional to the Inclusion Index, which is explained as a degree of commonly shared keywords between two theme clusters. The solid line links indicate the linked theme cluster sharing the main keywords vis-à-vis topics whereas, the broken line links indicate the theme clusters sharing keywords vis-à-vis topics that are not the main item.

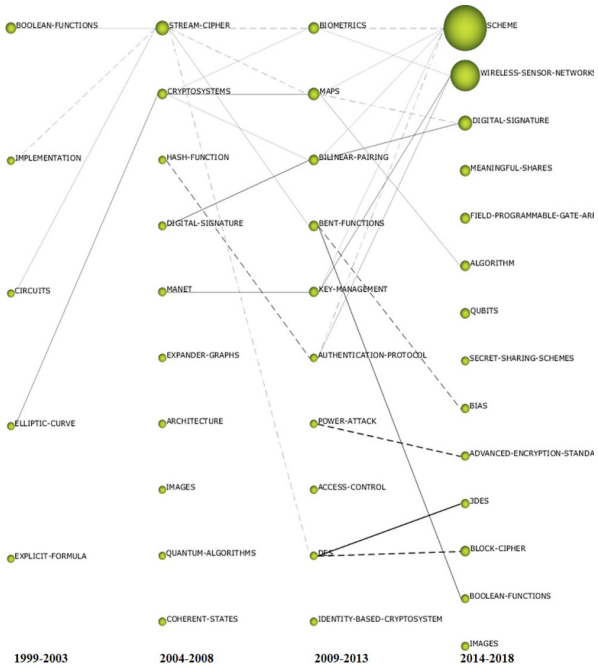


Figure 19: Evolution of themes in Indian cryptography research during successive periods.

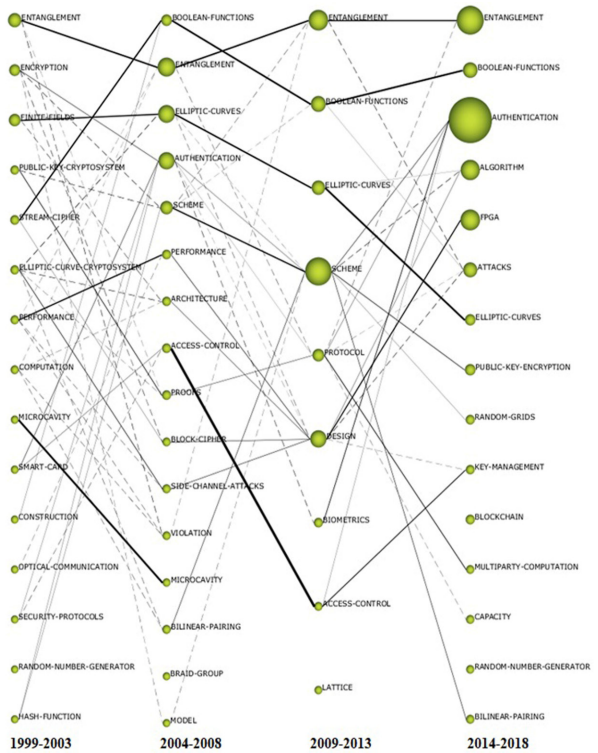


Figure 20: Evolution of themes in global cryptography research during successive periods.

In case of Indian cryptography research, three themes namely "BOOLEAN-FUNCTIONS", "CIRCUITS" and "ELLIPTIC-CURVE" have solid links with the themes of the next period that indicates the continuity of the associated keywords vis-à-vis topics. Although these themes have not appeared during the next period. During 2004-2008 the themes "STREAM-CIPHER", "CRYPTOSYSTEMS", "DIGITAL-SIGNATURE" and "MANET" represent transition themes that shared the main topics. The themes "STREAM-CIPHER" and "CRYPTOSYSTEMS" have changed over from the first period, whereas "DIGITAL-SIGNATURE" and "MANET" were found to have newly emerged. The theme "HASH-FUNCTION" also arose newly during the second period and while having a broken link with the theme "AUTHENTICATION-PROTOCOL" from the next period. The theme "STREAM-CIPHER" has acted as a thematic bridge that received topics from three themes of the previous period as well as shared its main topics with "BENT-FUNCTIONS" and associated topics with the other three themes of the next period. During 2009-2013 eight themes had appeared as transition themes among these seven have shared the main topics with the themes of the last period (2014-2018). It has been observed that the themes "BIOMETRICS", "SCHEME", "MAPS", "KEY-MANAGEMENT" and "AUTHENTICATION-PROTOCOL" have shared main topics and sub-topics only with the following themes, "SCHEME", "WIRELESS-SENSOR-NETWORKS", "DIGITAL-SIGNATURE", "ALGORITHM" from the last period.

In the case of global cryptography research, nine themes namely "ENTANGLEMENT", "ENCRYPTION", "FINITE-FIELDS", "PUBLIC-KEY-MANAGEMENT", "STREAM-CIPHER", "ELLIPTIC-CURVE-CRYPTOGRAPHY", "PERFORMANCE" and "MICROCAVITY" have a solid link with the themes of the next period that indicate the continuity of the associated keywords vis-à-vis topics. Among these themes, only three themes have appeared during the next period namely "ENTANGLEMENT", "PERFORMANCE" and "MICROCAVITY". During 2004-2008 the themes "BOOLEAN-FUNCTIONS", "ELLIPTIC CURVES", "SCHEME", "ACCESS-CONTROL", "PROOFS", "SIDE-CHANNEL-ATTACKS" and "BILINEAR-PAIRING" represented as transition themes sharing the main topics.

The theme "BRAID-GROUP" has also newly arisen during 2004-2008. During 2009-2013 fix themes namely, "ENTANGLEMENT", "BOOLEAN-FUNCTIONS", "ELLIPTIC CURVES", "SCHEME", "DESIGN" and "ACCESS-CONTROL", have acted as a thematic bridge those have received topics from the previous period as well as shared its main topics of the next period. The theme "LATTICE" also arose during 2009-2013. During the last period, "AUTHENTICATION" has become the main topic followed by "ENTANGLEMENT", "ALGORITHM", "FPGA", "BOOLEAN-FUNCTIONS" and "ATTACKS". Some themes during the period 2009-2013 have transformed into new themes during 2014-2018 namely, "ALGORITHM", "ATTACKS", "PUBLIC-KEY-ENCRYPTION", "RANDOM-GRIDS", "KEY-MANAGEMENT", "MULTIPARTY-COMPUTATION", "CAPACITY", "BILINEAR-PAIRING". The themes "BLOCK-CHAIN" and "RANDOM-NUMBER-GENERATOR" have newly emerged during 2014-2018.

Continuity of themes

Figure 19 and Figure 20 illustrate how the themes are distributed from 1999-2003 to 2014-2018 periods in Indian and global context. In case of Indian research, distribution and trend of carryover indicate a tendency of discontinuity of themes. It has been observed that none of the themes were omnipresent in every period and that most of the themes had newly arisen in each period. A very few themes have appeared at intervals although, their document frequency and citation impact were very found to be low. The theme "BOLEAN-FUNCTIONS" was the main theme during the initial period which has also appeared during the last period. The themes "DIGITAL-SIGNATURE" and "IMAGES" have appeared during second and last periods whereas "DIGITAL-SIGNATURE" was quite significant in both the periods as compared to the theme "IMAGES". In case of global research, distribution and trend of carryover show a tendency of continuity in the themes. Most of the themes have merged with other themes and had appeared as a new theme. The theme "ENTANGLEMENT" was the main theme during the initial period and it also appeared during the last period. A similar trend was also observed for "BOOLEAN-FUNCTIONS" and "ELLIPTIC-CURVES".

DISCUSSION

India secured 3rd position in cryptography research by contributing in nearly 10% of the total global publications. But based on ACPP and *h*-index data, India ranked the last among the top 10 countries. Increment of bibliometric parameters of Indian publications at higher CAGR indicates that cryptography research has received great importance at successive periods in India. The mean total citation per year has gradually decreased except in the last period which designates the impact of publications enhanced during the last period. The growing trend of the *h*-index indicates that the number of important Indian publications has increased at successive periods; however the proportion to the total publications has decreased. This is also supported by the frequency distributions among different citation categories at consecutive periods.

The top 20 Indian organizations have contributed to about one-third of the total Indian publications on cryptography research. The highest publishing organization has not received the highest ACPP and there is a very negligible correlation (R=0.01) between the number of publications and ACPP. Although there is a relatively strong correlation between publication numbers and *h*-indices (R=0.56) of the top 20 organizations. The top 20 authors have individually contributed more than 20 publications each. Similar trends like that have been observed in the organizations, that authors who have secured a leading position based on the number of publications have not secured a leading position based on citation impact. There is a very little negative correlation (R= -0.01) between the number of publications and ACPP of the top 20 Indian authors. Although there is a relatively moderate correlation between publication numbers and *h*-indices (R=0.23) of the top 20 authors.

Indian authors have contributed a lower share of publications in global top 20 source titles than the total global publication share. Among the top 20 source titles, Indian authors have contributed significantly to two source titles, viz., "Communications in Computer and Information Science" and "Advances in Intelligent Systems and Computing", with 36% and 29.72% share of total global publications, respectively. Top 20 source titles have contributed to 26.91% of the total Indian publications and these publications also received higher citation impact than the total Indian publications.

The multinational collaborations in cryptography research have played a significant role to enhance the quality of Indian publications. It has been observed that 10% of the total Indian publications were collaborative in nature and these publications received more than 30% of the total citations. Therefore, the ACPP of collaborated publications was more than four times higher. The calculated 5-year impact factor of collaborated publications was also higher throughout the study periods. Indian research work published without any international collaboration scored maximum frequency distributions (88.20%) among the 'no citation' and '1-5 citation' categories, whereas, it was only 54.52% for the collaborated Indian publications. Besides this, the publication distributions were fairly good in higher citation categories for the publications coming out of collaborations. Indian authors have published in 32.14% of total collaborated publications with USA that happens to be the 2nd leading country in this field.

The strategic maps have represented the most important well-developed themes, marginally important isolated themes, emerging or declining themes and weakly-developed basic themes during successive periods. In case of India, "BOOLEAN-FUNCTIONS" was the most frequent theme during the initial period that played an important role in cryptography, mainly in the designing of symmetric key algorithms. During the next period (2004-2008) the theme "STREAM-CIPHER" was the most frequent and central theme, that deals with the encryption of a text to generate ciphertext. During 2009-2013 the themes "BIOMETRICS", "SCHEME" and "MAPS" were the most frequent and central themes. During the last period the theme "SCHEME" was the most frequent and central theme and "WIRELESS-SENSOR-NETWORKS" was the 2nd most frequent but basic and poorly developed theme. Keywords overlapping map has quantitatively explained the emergence of new keywords as the Indian cryptography research has been expanded at consecutive periods. The higher proportion of newly added keywords of Indian publications as compared to the global publications designates diversification of research topics at successive periods, although the number of keywords was less compared to the global context. The comparative thematic evolution maps indicated that the themes of the Indian cryptography research were inconsistent at consecutive periods compared to the global cryptography research. New themes have appeared as important themes during successive periods which indicated the Indian cryptography research was diversified consistently. Although the most frequent and central themes of Indian research were not similar to the global cryptography research at successive periods. Interestingly, some of the latest global themes like "ENTANGLEMENT", "PUBLIC-KEY-ENCRYPTION", "RANDOM-GRIDS", "BLOCKCHAIN", "MULTIPARTY-COMPUTATION", "RANDOM-NUMBER-GENERATOR"and"CAPACITY", never appeared in Indian cryptography research themes. Although some work was certainly published in these areas and have contributions in sub-thematic network of various major themes of Indian cryptography research.

CONCLUSION AND FUTURE PROSPECT

This study investigated the performance of Indian cryptography research quantitatively as well as qualitatively during 1999-2018. A detailed analysis of bibliometric parameters showed that the cryptography research performance has accelerated at a higher CPGR during the last decade. The citation impact of Indian research publications was the lowest among the top 10 countries although, India ranked 3rd based on the number of publications. This study also identified the most proficient Indian organizations and authors, which might be helpful in establishing further links among organizations and authors for the sake of advancement through co-operation, resulting in constructive output. Information about top source titles will be helpful to design future research and to identify source titles for research communication. Research collaboration in this field played a significant role to improve the quality of Indian research on cryptography. Therefore, more collaborative research in this field will boost the quality and quantity of

Indian cryptography research. The quantitative and qualitative thematic analyses through strategic maps revealed the periodic progression of Indian research in this field. Additionally, the comparative thematic evolution analysis between global and Indian research during successive periods identified strength and lacuna of Indian research in this field. The highest degree of discontinuity of research themes and the lowest degree of connection bridges among research themes have hindered the research up-gradation in Indian cryptography compared to the global context. This comparative analysis suggests some recent global research themes, namely "ENTANGLEMENT", "PUBLIC-KEY-ENCRYPTION", "RANDOM-GRIDS", "BLOCKCHAIN", "MULTIPARTY-COMPUTATION", "RANDOM-NUMBER-GENERATOR" and "CAPACITY", which are required to be addressed in order to transform into major themes for further advancement in Indian cryptography research.

ACKNOWLEDGEMENT

Saheli Pal Dutta is grateful to the National Science & Technology Management Information System, Department of Science and Technology (NSTMIS-DST), Government of India for providing fellowship to pursue research. All the authors are thankful to Dr. Abhishek Das for performing an extensive editing of the manuscript. All the authors are grateful to Bose Institute, India for providing access to various databases and websites.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ABBREVIATIONS

ATM: Automated teller machine; **WoS:** Web of Science; **MASS:** Mobile Application Security System; **IoT:** Internet of Things; **ECC:** elliptic curve cryptosystem; **ACPP:** Average citation per publication; **NP:** Number of publications; **DF:** Document frequency; **CPGR:** Compound period-wise growth rate.

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