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Mapping of Indian computer science research output, 1999–2008

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Abstract The research output of India in computer science during 1999–2008 is analyzed in this paper on several parameters including total research output, its growth, rank and global publication share, citation impact, share of international collaborative papers and major collaborative partner countries and patterns of research communication in most productive journals. It also analyses the characteristics of most productive institutions, authors and high-cited papers. The publications output and impact of India is also compared with China, South Korea, Taiwan and Brazil.

Keywords Computer science · Information technology · Mapping · Research priorities in computer

Introduction

Computer has penetrated all strata of the modern society. In fact, among all technologies, which have emerged in the twentieth century, none has such a profound impact as the computer. Computer, in turn, has given birth to a new industry broadly labeled as Information Technology (IT). IT has been defined by the Information Technology Association of America (ITAA) as being the study, design, development, implementation support and/

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or management of any computer based information systems. This relates particularly to software applications and computer hardware. IT deals with using electronic computers and software to convert, store, protect, process, retrieve with security or transmit any information. What began many years ago as a term that many had no awareness of to a term that has skyrocketed to include several aspects of computing and technology. IT is a wide based term and encompasses many areas. Professionals in IT may perform a wide variety of tasks that range from installing computer applications to designing widely complex computer networks and information databases (http://ezinearticles.com/?Defination-of-Information-Technology).

Over the years, India has emerged as a important IT player in the world. There is a strong national, political, and administrative commitment to IT as a priority sector. According to the National Association of Software and Service Companies (NASSCOM), the apex body for software services in India, the revenue of the IT sector has risen from 1.2% of the gross domestic product (GDP) in FY 1997–1998 to an estimated 5.8% in FY 2008–2009. The Government of India has constituted a new Ministry of Information Technology. Realizing the special importance of IT, the Prime Minister of India gave a call to make India an IT superpower in the world within next 10 years. As an initiating step in this regard, a high-powered National Task Force on Information Technology and Software Development was set up by the Prime Minister's Office on May 22, 1998, under the Chairmanship of the Deputy Chairman of Planning Commission. This taskforce formulated the draft National Informatics Policy. It addressed several different issues such as national information infrastructure, IT driven governance, IT education especially at college and secondary school level, information content on internet, laws and regulations for cyberspace, IT research and development, and IT manpower development, etc (http://informatics.nic.in/archive/july1998.pdf; http://ittaskforce.nic.in.minutes.htm). The government also enacted the Information Technology Act, which provides a legal framework to facilitate electronic commerce and electronic transactions. The government-led National e-Governance Programme, has played an important role in increasing internet penetration in rural India. The State Governments are also enunciating their IT policies. Many States are now vying with each other to develop their own brands of Silicon Valleys as hubs of IT activities. All these developments had a tremendous impact on computer education and training at all levels. Computer and IT education and training have grown into a big industry.

The educational and training institutions in the field of computer science and technology may be grouped into formal and informal sectors. The formal sector comprises schools, vocational institutions and polytechnics, and institutions within the university system and institutes of national importance. Viz, IITs, and Indian Statistical Institutes, Kolkata, University Departments of Computer Science, and colleges affiliated to universities. It also covers institutions outside the university system, viz, training institutions recognized by the All India Council for Technical Education (AICTE), including the newly established Indian Institute of Information Technology (IIITs) in several states, and the Department of Electronics and Accreditation of Computer Courses (DOEACC) accredited training institutes. They offer programs at various hierarchical levels—certificate, diploma, post-diploma, graduation, post-graduation—and finally, at the doctoral level. The informal sector consists of a large number of private enterprises spread across the country, often referred to as training "vendors", which offer a perplexing variety of courses.

A large number of institutes from academic sector, R&D sector, government sector and private sector are involved in computer science research with support of government funds. These organizations are involved in a wide breadth of research problems under all major areas of computer science. Besides spending a considerable amount of money on

infrastructure development and R&D activities on their own, these organizations are also getting enormous funds by way of extramural support from several government R&D agencies, including Ministry of Information Technology (MOIT), Department of Electronics (DoE), Defence Research and Development Organization (DRDO), Department of Atomic Energy (DAE), Department of Space (DoS), All India Council of Technical Education (AICTE), Ministry of Human Resource Development and University Grants Commission (UGC). R&D has been identified as a thrust areas under the Ministry of Information Technology. This support has helped in building infrastructure and competencies at a large number of academic and research institutions, produced the required manpower to take up R&D in the industry, besides development of various products and packages.

India has become the global mark for IT professionals because of dedicated hard work and effective IT strategies of the IT companies. Some of the key in IT-ITES sector are: Infosys Technologies, Tata Consultancy Services (TCS), Wipro Technologies, etc. In addition a number of foreign firms have established R&D centers in India.

Literature review

India has been edged out by China in the Network Readiness Index (NRI) ranking according to the "The Global Information Technology Report 2008–2009" (http://www.topnews.in/global_information_technology_report_20082009_ranks_india)54thplace_2146003). India has fallen from the 50th place in 2007–2008 to the 54th position, while China has been able to occupy the 46th position. India has been continuously slipping down in the NRI ranking; India's was at 44th position in 2006–2007 in GIT report. On the contrary, China's has showed phenomenal 11 positions jump in the latest ranking. The speed at which China is transforming its IT infrastructure through a combination of human development and technology-related policies have brought a massive change among the BRIC countries for the first time. According to a more recent Economic Intelligence Report on IT Competitiveness (The Economist, Economic Intelligence Unit 2009), the country IT competitiveness depends upon a number of factors such as quality of local technology infrastructure, the availability and quality of talent, the innovation environment, the legal regime, overall business environment, as well as government technology policy. The report has worked out an overall IT competitiveness of countries by giving different weights to business environment (10%), IT infrastructure (20%), human capital (20%), R&D environment (25%), legal environment (10%) and support for IT industry development (15%). According to this report, India's overall score in IT competitiveness was 34.1 (up from its score of 44 in 2008) in 2009, compared to 36.7 for China and 36.6 for Brazil. In terms of individual factors, India score during 2009 was business environment (59.0% for India, compared to 48.8% for China and 73.6% for Brazil), IT infrastructure (1.9 for India, compared to 13.8 for China and 21.6 for Brazil), human capital (49.5 for India, compared to 57.9 for China and 49.5 for Brazil), R&D environment (22 for India, compared to 23.2 for China and 17.6 for Brazil), legal environment (48 for India, compared to 59.5 for China and 49.5 for Brazil) and support for IT industry development (51 for India, compared to 39.2 for China and 61.6 for Brazil) (http://informatics.nic.in/archive/july1998.pdf; http://ittaskforce.nic.in.minutes.htm). Another study compares the scientific research competitiveness of 233 world universities in computer science by Ma et al. (2008), using the primary indicators of scientific research production (papers), scientific research influence (total citations and high cited papers), scientific research innovation (hot papers) and scientific research development (ratio of high cited papers to total papers and average citations per paper) and later weights are assigned to each of these indicators depending upon their importance. The study looks at 233 university computer science

departments from 23 countries, 127,418 published papers, 468,244 citations, 1,856 highly cited papers and 57 *hot* papers over the last 10 years (1.1.1996–8.31.2006) using data from Thomson-ISI. According to this study, in overall competitiveness of countries (by combining data of their universities in the sample) in computer science, USA holds the first rank, followed by UK, Canada, Denmark, Israel, Germany, etc. China-Taiwan holds the 16th rank, followed by Singapore (19th rank), South Korea (23rd rank), China (24th rank) and India (26th rank).

Das and Kranzai (2002) analyzed the contribution of leading Indian institutions in computer science, based on 1,408 Indian papers published during 1991–2000 as covered in *Science Citation Index*. Gupta and Dhawan (2005) studied 4,690 Indian computer science papers published during 1994–2001 as covered in INSPEC database, focusing on publication output and quality, identification of areas of strength and weakness and contribution of leading institutions and individual scholars. Suresh Kumar and Garg (2005) analysed 2,058 Chinese and 2,678 Indian computer science papers published during 1971–2000, focusing on the (i) distribution of papers in local and international journals, (ii) distribution of papers by impact IF range and coverage in SCI versus Non-SCI covered journals, and (iii) the extent of collaboration, based on the data derived from a number of published computer science bibliographies. Gu (2002) studied productivity of 461 Malaysian publications in computer science and IT published during 1990–1999, as covered in three web-based databases. Guan and Ma (2004) analyzed the comparative performance of India and China with four other major western countries, based on 9,632 computer science papers published during 1993–2002, as covered in INSPEC database. Besides research output and quality, other scientometric indicators used are normalized impact factor and ratio of papers in high quality journals are further adopted to analyze research performance of India and China. He and Guan (2008) analysed the contribution of China in computer science as reflected in conference proceedings series book—*Lecture Notes in Computer Science* (*LNCS*) during 1997–2005 in terms of growth, collaboration and impact. Wainer et al. (2009) compared the computer science output of Brazil with several other countries in terms of ratio of number of papers in journals and conference proceedings, as indexed by ISI and Scopus database during 2001–2005.

Objectives

The main objective of this study is to analyze the research performance of India in computer science research in national and global context, as reflected in its publication output during 1999–2008. In particular, the study focuses on the following objectives: (i) To study the Indian research output, its growth, rank and global publication share and impact, (ii) To study the patterns of international collaboration, (iii) To study the publication productivity and impact of leading institutions of India, (iv) To study the characteristics of prolific authors and high cited-papers, and (v) To study the patterns of research communication in most productive journals.

Methodology and source of data

This study is based on the Indian publication data in computer science retrieved from the Scopus Citation database for the 10 years (1999–2008). Three-year citations window has been used for counting the citations received and to access the impact of Indian research

output, leading Indian institutions and authors and international collaborative papers. The Scopus classified the entire S&T literature under four broad fields (physical, life, engineering and health sciences) and 20 narrow fields including computer science. The study is limited to the literature covered under computer science. There is a overlapping of journal coverage under the 20 narrow subject fields. The authors have identified 11 sub-fields using a keyword strategies developed at their own end. For keywords finally selected used, the keywords used are listed in Appendix 1.

The process used in keyword selection was as follows. First a general query on Indian computer science research from 1999 to 2008, using the following search strategy was used: "affil (india) and pubyear aft 1998 and pubyear bef 2009 and (limit-to (subjarea, "comp"))". This query additionally generated a set of 160 leading keywords with the frequency of their occurrence varying from 133 to 2,195. Then the Indian computer science experts were consulted for choosing the most important keywords relevant to the 11 sub-fields defined. The list of keywords generated from the database was sent to 50 Indian experts with a request to relate these keywords to these 11 sub-fields and also suggest new keywords not existing in the list of keywords sent. On the basis of expert's advice, the keywords relevant to the 11 sub-fields were finalized.

For citation data, each publication year was subjected to 3 years citation window. And then the entire publication and citation data is cumulated. For calculating the total international collaborative papers in computer science, a separate search strategy, which combines India's collaboration with 140 major countries, was prepared and this string was combined with the main string to generate India's total international collaborative output.

For analyzing institutional, authors and journals output, the separate institutional, author and journal output strategies strings were evolved and these strings later were combined with the main string. For generating high-cited papers, the main string is first run. Then, the tag "citation to" is ticked, which rearranges the entire output in the decreasing order of citations received by each paper with most high-cited papers at the top. Then the top 100 most high-cited papers are marked and downloaded for analyses.

Analysis

Global publication share and rank

In overall, the global publication shares of the top 24 countries vary from 0.65 to 18.48% during 1999–2008. The United States tops the list with global publication share of 18.48% during 1999–2008. The China ranks second, followed by Japan, UK, France, Canada, South Korea and Italy (their global publication share ranging from 3.42 to 13.60%). Taiwan, Spain, and Australia rank at 10th to 12th positions (their global publication share ranging from 2 to 3%). The countries that rank between 13th and 20th positions are India, Netherlands, Singapore, Switzerland, Brazil, Israel, Poland and Brazil with their global publication share ranging from 1 to 2%). The next four countries (Russia, Turkey, Colombia and Mexico) ranks from 21st to 24th positions with their global share less than 1% (Table 1).

Among developed countries, the countries that have shown decline in publication share from the year 1999 to the year 2008 are United States by 19.76% (decreasing from 33.04 to 13.28%), followed by Japan by 3.88% (from 9.04 to 5.16%), United Kingdom by 1.51% (from 6.30 to 4.78%), Canada by 0.81% (from 4.47 to 3.67%), Germany by 0.75% (from 5.72 to 4.97%), Russia by 0.71% (from 1.38 to 0.67%) and Italy by 0.46% (from 3.63 to

Table 1 Global publication output, publication share and rank of top 24 most productive countries in computer sciences, 1999–2008

S.No.	Country	No. of papers			% Share of papers			Rank		
		1999–2008	1999	2008	1999–2008	1999	2008	1999–2008	1999	2008
1	USA	171,408	13,964	27,808	18.48	33.04	13.28	1	1	2
2	China	126,140	1,607	45,705	13.60	3.80	21.83	2	7	1
3	Japan	53,249	3,821	10,807	5.74	9.04	5.16	3	2	3
4	UK	50,678	2,661	10,012	5.46	6.30	4.78	4	3	5
5	Germany	46,675	2,419	10,412	5.03	5.72	4.97	5	4	4
6	France	40,320	1,823	9,024	4.35	4.31	4.31	6	6	6
7	Canada	37,549	1,891	7,676	4.05	4.47	3.67	7	5	7
8	South Korea	32,711	1,003	6,661	3.53	2.37	3.18	8	10	9
9	Italy	31,765	1,536	6,637	3.42	3.63	3.17	9	8	10
10	Taiwan	26,021	1,177	6,718	2.81	2.78	3.21	10	9	8
11	Spain	25,049	777	5,630	2.70	1.84	2.69	11	11	11
12	Australia	20,519	694	4,692	2.21	1.64	2.24	12	12	12
13	India	15,924	582	4,677	1.72	1.38	2.23	13	16	13
14	Netherlands	15,153	685	3,203	1.63	1.62	1.53	14	13	14
15	Singapore	12,355	483	2,632	1.33	1.14	1.26	15	17	15
16	Switzerland	10,716	418	2,242	1.16	0.99	1.07	16	18	18
17	Brazil	10,132	373	2,484	1.09	0.88	1.19	17	20	16
18	Israel	9,740	612	1,705	1.05	1.45	0.81	18	14	20
19	Poland	9,344	262	2,259	1.01	0.62	1.08	19	22	17
20	Belgium	9,288	397	1,954	1.00	0.94	0.93	20	19	19
21	Russia	7,896	583	1,407	0.85	1.38	0.67	21	15	23
22	Turkey	6,500	189	1,509	0.70	0.45	0.72	22	24	22
23	Colombia	6,460	337	1,229	0.70	0.80	0.59	23	21	24
24	Mexico	5,993	227	1525	0.65	0.54	0.73	24	23	21
	World	927,516	42,269	209,397						

3.17%). In contrast, the developed countries that have shown rise in their publication share during the same period are Spain by 0.85% (from 1.84 to 2.69%), Australia by 0.60% (1.64 to 2.24%), Poland by 0.46% (from 0.62 to 1.08%) and Turkey by 0.27% (from 0.45 to 0.72%).

In contrast, most developing countries (except Columbia) have shown rise in their publication share from the year 1999 to the year 2008: China by 18.03% (increasing from 3.80 to 21.83%), India by 0.86% (from 1.38 to 2.23%), South Korea by 0.81% (from 2.37 to 3.18%), Taiwan by 0.42% (from 2.78 to 3.21%), Brazil by 0.30% (from 0.88 to 1.19%), Mexico by 0.19% (from 0.54 to 0.73%) and Singapore by 0.11% (from 1.26 to 1.33%) (Table 1).

India ranks at 13th position among the top 24 most productive countries in computer science, with its global publication share of 1.72% during 1999–2008. Compared to India, China, South Korea, Taiwan, Singapore, Brazil and Mexico ranks at 2nd, 8th, 10th, 15th, 17th and 24th positions with global publication share of 13.60, 3.53, 2.81, 1.33, 1.09 and 0.65% during 1999–2008. India's global ranking has improved from 16th to 13th from the

year 1999 to the year 2008. Compared to India, China global rank has increased from 7th to 1st, South Korea from 10th to 9th, Taiwan from 9th to 8th, Singapore from 17th to 15th, Brazil from 20th to 16th and Mexico from 23rd to 21st.

The annual average publication growth rate of world publication output during 1999–2008 was 20.37%. Among the top 24 most productive countries, the developed countries that have shown less than the world average annual growth rate are United States with 8.88% annual growth rate, followed by Russia (11.92%), Japan (14.08%), UK (16.73%), Canada (18.08%), Italy (18.90%), Netherlands (19.90%) and Germany (19.92%). In contrast, the developed countries that have scored more than the world average annual growth rate are France with annual average growth rate of 21.24%, followed by Belgium (22.04%), Switzerland (23.96%), Australia (25.45%), Spain (27.19%) and Belgium (31.64%), as seen from annual research output of papers published during 1999–2008. In contrast to developed countries, most developing countries (with the exception of Colombia and Israel) among the top 24 most productive countries have shown higher average annual growth than world average, with maximum (47.92%) recorded by China, followed by India (28.68%), Mexico (27.38%), South Korea (25.92%), Brazil (25.75%), Singapore (21.49%), as seen from annual research output of papers published during 1999–2008.

The cumulative publications output of top 24 most productive countries in computer science during 1999–2008 was also compared with their population (in millions, 2009) and Gross Domestic Product (PPP, US $, 2009). On per capita basis, Singapore produced the highest number of publications (2480.92) per million inhabitants during 1999–2008, followed by Switzerland with 2nd rank and 1377.38 publications, Israel with 3rd rank and 1284.96 publications, etc. Among the developing countries, Taiwan is on the top with 4th rank and 1124.99 publications per million inhabitants, followed by South Korea (10th rank, 657.24 publications), China (19th rank, 94.27 publications) Brazil (23rd rank, 52.48 publications) and India (24th rank, 13.47 publications) (Table 2).

On taking the ratio of publications and GDP, Singapore again tops the list with first rank and 52.42 publications, followed by Israel (2nd rank, 47.10 publications), Taiwan (3rd rank, 36.26 publications), Switzerland (4th rank, 33.80 publications), etc. Among developing countries, Taiwan tops the rank, followed by South Korea (8th rank, 24.12 publications), China (16th rank, 14.35 publications), Brazil (21st rank, 5.0 publications) and India (22nd rank, 4.47 publications) (Table 2).

India's publication output in computer science

India total cumulative publications output in computer science consists of 15,924 papers during 1999–2008, with average number of papers per year as 1,592. Compared to India, the cumulative publications output of China during the same period consists of 126,140 papers, followed by South Korea (32,711 papers), Taiwan (26,021 papers) and Brazil (10,132 papers), with average number of papers per year as 12,614 of China, followed by South Korea (3,271), Taiwan (2,600) and Brazil (1,013). The cumulative publications output of India has increased from 3,315 papers to 12,609 papers from 1999–2003 to 2004–2008, witnessing a growth of 280.36% growth (Table 3).

Compared to India, the cumulative publications output of China increased from 13,911 papers to 112,229 papers (with a growth rate of 706.76%) from 1999–2003 to 2004–2008), followed by South Korea from 7,379 papers to 25,332 papers (with a growth rate of 243.30%), Taiwan from 6,802 papers to 19,219 papers (with growth rate of 182.55%) and

Table 2 Publications, population and gross domestic data of top 24 most productive countries

S.No.	Country	No. of publications, 1999–2008	Population* 2009 (million)	GDP (PPP) (2009) US $ (billion)	Publication per capita	Publications per GDP
1	USA	171,408	309.47	14,260	553.88	12.02
2	China	126,140	1338.01	8,789	94.27	14.35
3	Japan	53,249	127.36	4,137	418.10	12.87
4	UK	50,678	62.04	2,149	816.86	23.58
5	Germany	46,675	81.76	2,811	570.88	16.60
6	France	40,320	65.45	2,110	616.04	19.11
7	Canada	37,549	34.13	1,285	1100.18	29.22
8	South Korea	32,711	49.77	1,356	657.24	24.12
9	Italy	31,765	60.34	1,760	526.43	18.05
10	Taiwan	26,021	23.13	717.7	1124.99	36.26
11	Spain	25,049	46.03	1,368	544.19	18.31
12	Australia	20,519	22.38	824.3	916.85	24.89
13	India	15,924	1181.98	3,560	13.47	4.47
14	Netherlands	15,153	16.62	654.9	911.73	23.14
15	Singapore	12,355	4.98	235.7	2480.92	52.42
16	Switzerland	10,716	7.78	317.0	1377.38	33.80
17	Brazil	10,132	193.06	2,025	52.48	5.00
18	Israel	9,740	7.58	206.8	1284.96	47.10
19	Poland	9,344	38.16	690.1	244.86	13.54
20	Belgium	9,288	10.83	381.0	857.62	24.38
21	Russia	7,896	141.93	2,116	55.63	3.73
22	Turkey	6,500	72.56	863.0	89.58	7.53
23	Colombia	6,460	45.48	401.0	142.04	16.11
24	Mexico	5,993	107.55	1,482	55.72	4.04

Population as on 2009–2010 http://en.wikipedia.org/wiki/List_of_countries_by_population; GDP (PPP) (2009) http://www.cia.gov/library/publications.the_world_factbook/rankorder/2001.rank.html

Brazil from 2,474 papers to 7,658 papers (with growth rate of 209.54%), as against growth of 146.18% of the world cumulative publication output during the same period (Table 4).

In terms of impact and quality, the average citations per paper registered by India's publications output during 1999–2006 were 2.10. The average citations per paper for India's cumulative publications decreased from 2.31 during 1999–2002 to 2.01 during 2003–2006 (Table 3). The h-index registered by all Indian papers during 1999–2008 was 60.

International collaboration in India's publication output

Based on the publications data, the total cumulative collaborative papers output during 1999–2008 consist of 3,173, which contributed 19.92% share are in the cumulative output of India in computer science of India. Compared to India, Brazil's international collaborative papers share in its cumulative publication output during 1999–2008 was 28.10% (with 2,847 collaborative papers), followed by South Korea with 15.99% share (with 5,230

Table 3 Growth and impact of Indian publications in computer science, 1999–2008

Year	TP	TC	ACPP	Year	TP	TC	ACPP
1999	592	1,159	1.96	2006	2,302	2,594	
2000	681	1,219	1.79	2007	3,150		
2001	541	1,185	2.19	2008	4,777		
2002	622	2,077	3.34	1999–2003	3,315		
2003	879	2,279	2.59	2004–2008	12,609		
2004	1,158	3,080	2.66	1999–2008	15,924		1.13
2005	1,322	3,424	2.59				

TP total papers, *TC* total citations, *ACPP* average citations per paper

Table 4 Annual growth of publications of China, South Korea, Taiwan and Brazil in computer science, 1999–2008

Period	Number of publication, 1999–2008			
	China	South Korea	Taiwan	Brazil
1999	1,607	1,003	1,177	373
2000	1,921	1,133	1,395	407
2001	2,877	1,199	1,286	464
2002	2,639	1,339	1,253	481
2003	4,867	2,705	1,791	749
2004	7,354	3,136	1,938	934
2005	13,033	4,162	2,347	880
2006	19,342	5,472	3,299	1,552
2007	26,795	5,901	4,817	1,808
2008	45,705	6,661	6,718	2,484
1999–2003	13,911	7,379	6,902	2,474
2004–2008	112,229	25,332	19,119	7,658
1999–2008	126,140	32,711	26,021	10,132

collaborative papers), Taiwan with 11.33% share (with 2,948 collaborative papers) and China with 10.42% share (with 13,160 collaborative publications).

India witnessed a substantial decrease in the share of international collaborative papers from 24.95% (827 papers) during 1999–2003 to 18.60% (2,346 papers) during 2004–2008. Compared to India, the international collaborative publications share of South Korea has increased from 14.59 to 16.39%, Taiwan from 10.21 to 11.73% and Brazil from 25.75 to 29.15%, as against decrease from 12.69 to 10.15% in case of China from 1999–2003 to 2004–2008 (Table 5).

Among the India's major collaborating partners, the largest share (47.70%) of collaborative papers during 1999–2008 was with United States, followed far behind by United Kingdom, Canada, Germany, Singapore, France and Japan (with publications share from 5.34 to 8.62%), Australia, South Korea, Italy, Malaysia, China and Switzerland (with publications share from 2.05 to 4.30%), Netherlands, Georgia, Norway, Taiwan, Spain, Sweden, Israel, Finland, Belgium, Denmark and Mexico (with publications share from 1.01 to

Table 5 Number and share of international collaborative publications in computer science during 1999–2008

Country	No. of international collaborative papers			Share of international collaborative papers		
	1999–2003	2004–2008	1999–2008	1999–2003	2004–2008	1999–2008
India	827	2,346	3,173	24.95	18.60	19.92
China	1,766	11,394	13,160	12.69	10.15	10.43
South Korea	1,077	4,153	5,230	14.59	16.39	15.99
Taiwan	705	2,243	2,948	10.21	11.73	11.33
Brazil	637	2,210	2,847	25.75	29.15	28.10

1.80%), and the rest below 1% publication share. Among these collaborating partners of India, the share of international collaborative publications have decreased in case of United States, Germany, Singapore, Japan, China, Netherlands, Israel and Denmark from 1999–2003 to 2004–2008, in contrast to increase in all other countries during the same period (Table 6).

Sub-fields of research priority in computer science research in India

As per the sub-fields cumulative output in Indian computer science research during 1999–2008, the maximum research priority (4,846 publications, 30.43% share) is assigned to computer software in India during 1999–2008, followed by computer networks (3,967 publications, 24.91% share), artificial intelligence (2,394 publications, 15.03% share), cryptology and computer hardware (721 publications, 4.53% share each), database management system (543 publications, 3.41% share), software engineering (516 publications, 3.24% share), computer theory (504 publications, 3.17% share), internet and multi-media (499 publications, 3.13% share), computer architecture (284 publications, 1.78% share) and operating systems (169 publications, 1.06% share).

Out of 11 sub-fields identified above, only three sub-fields witnessed increase in their activities from 1999–2003 to 2004–2008 as reflected in their activity index: computer networks (from 72.65 to 107.19), software engineering (from 89.37 to 102.79) and operating systems (93.80 to 101.63). While in the remaining there is a relative decline in publication activity (Table 7).

Compared to India, the research priorities as reflected in distribution of paper by sub-fields in computer science in China, South Korea and Brazil during 1999–2008 are more or less same as shown in Table 7. The top research priority is assigned to three fields, namely computer software, computer networks and artificial intelligence with combined publication share of 70.38% in India, 62.93% in China, 69.08% in South Korea and 73.14% in Brazil during 1999–2008, followed by second priority to next five fields, namely internet and multimedia, computer hardware, database management systems, software engineering and computer theory with combined publication share of 23.76% in India, 17.75% in China, 28.53% in South Korea and 26.31% in Brazil and the third priority to next three fields namely computer architecture, cryptology and operating systems with combined publication share of 3.96% in India, 2.99% in China, 5.94% in South Korea and 4.00% in Brazil (Table 8).

The impact and quality of research output under various sub-fields was also studied in terms of citations received on the 3 years citations window. The maximum impact (3.10) was made by artificial intelligence, followed by computer software (2.97), cryptology (2.90), data base management system (2.74), internet and multimedia (2.72), computer

Table 6 Major collaborative country's share in total international collaborative papers (TICP) of India in computer science, 1999–2008

Country	Total international collaborative papers (TICP)			% Share of TICP		
	1999–2008	1999–2003	2004–2008	1999–2008	1999–2003	2004–2008
USA	1,509	504	1,005	47.70	60.94	42.97
United Kingdom	273	62	211	8.62	7.497	9.021
Canada	246	59	187	7.77	7.134	7.995
Germany	235	64	171	7.42	7.739	7.311
Singapore	191	51	140	6.03	6.167	5.985
France	188	36	152	5.94	4.353	6.499
Japan	169	45	124	5.34	5.441	5.301
Australia	136	19	117	4.30	2.297	5.002
South Korea	128	19	109	4.04	2.297	4.66
Italy	118	22	96	3.73	2.66	4.104
Malaysia	78	17	61	2.46	2.056	2.608
China	75	20	55	2.37	2.418	2.351
Switzerland	65	15	50	2.05	1.814	2.138
Netherlands	57	19	38	1.8	2.297	1.625
Norway	57	1	56	1.8	0.121	2.394
Georgia	57	11	46	1.8	1.33	1.967
Taiwan	53	11	42	1.67	1.33	1.796
Spain	48	10	38	1.52	1.209	1.625
Sweden	47	12	35	1.48	1.451	1.496
Israel	38	11	27	1.20	1.33	1.154
Finland	37	3	34	1.17	0.363	1.454
Belgium	36	8	28	1.14	0.967	1.197
Denmark	34	10	24	1.07	1.209	1.026
Belgium	36	8	28	1.14	0.967	1.197
Denmark	34	10	24	1.07	1.209	1.026
Poland	31	5	26	0.98	0.605	1.112
Mexico	32	7	25	1.01	0.846	1.069
Total	3,166	827	2,339			

networks (2.25), software engineering (2.16), computer architecture (2.11), computer hardware (2.05), computer theory (1.77) and operating systems (1.77). In terms of change in citation impact from 1999–2002 to 2003–2006, the sub-fields, which have improved their impact are: database management system (from 2.72 to 2.75), computer architecture (from 1.65 to 2.30), computer hardware (from 1.39 to 2.36), computer theory (from 1.75 to 1.78) and operating systems (from 1.57 to 1.83). In other fields, the impact has gone down from 1999–2002 to 2003–2006 (Table 9).

Research profile of productive Indian institutions

In this section, an analysis of top 30 most productive Indian institutions are presented, which have contributed papers from 96 to 1,241 during 1999–2008 in Indian computer

Table 7 India's research priorities in computer science research by sub-fields, 1999–2008

S.No.	Sub-fields	Number of papers			Activity index	
		1999–2003	2004–2008	1999–2008	1999–2003	2004–2008
1	Computer software	1,074	3,772	4,846	106.46	98.30
2	Computer networks	600	3,367	3,967	72.65	107.19
3	Artificial intelligence	508	1,886	2,394	101.93	99.49
4	Cryptology	181	540	721	120.59	94.59
5	Database management systems	133	410	543	117.66	95.36
6	Software engineering	96	420	516	89.37	102.79
7	Computer theory	108	396	504	102.93	99.23
8	Internet and multi media	198	301	499	190.60	76.18
9	Computer architecture	76	208	284	128.55	92.49
10	Operating systems	33	136	169	93.80	101.63
11	Computer hardware	181	540	721	120.59	94.59
	Total	3,315	12,609	15,924	100.00	100.00

There is some duplication in terms of coverage in 11 sub-fields. As a result, the total output of 11 sub-fields may be more than 100.0%

Table 8 Research priorities in computer science research by sub-fields in four developing countries, 1999–2008

S.No.	Subject sub-field	Number of papers				% Share of papers			
		India	China	South Korea	Brazil	India	China	South Korea	Brazil
1	Computer software	4,846	36,235	10,171	3,643	30.43	28.73	31.09	35.96
2	Computer networks	3,967	25,649	9,365	1,938	24.91	20.33	28.63	19.13
3	Artificial intelligence	2,394	17,492	3,061	1,830	15.03	13.87	9.36	18.06
4	Internet and multi media	1,499	9,988	4,580	818	9.41	7.92	14.00	8.07
5	Computer hardware	721	3,458	2,080	523	4.53	2.74	6.36	5.16
6	Database management systems	543	2,928	1,173	389	3.41	2.32	3.59	3.84
7	Software engineering	516	3,696	802	690	3.24	2.93	2.45	6.81
8	Computer theory	504	2,325	697	246	3.17	1.84	2.13	2.43
9	Computer architecture	284	1,397	953	266	1.78	1.11	2.91	2.63
10	Cryptology	177	1,215	469	45	1.11	0.96	1.43	0.44
11	Operating systems	169	1,154	521	94	1.06	0.91	1.59	0.93
	Total	15,924	12,6140	32,711	10,132				

There is some duplication in terms of coverage in 11 sub-fields. As a result, the total output of 11 sub-fields is more than 100%

science research. Of these 30 institutions, ten are institutes of national importance, 14 universities and colleges (eight universities, two deemed universities engineering colleges, one Indian Institute of Information Technology, one National Institutes of Technology/ Regional Engineering Colleges and two select engineering colleges), two Research Institutes and four Industrial Enterprises.

Table 9 Impact and quality of Indian computer science research by sub-fields, 1999–2006

S.No.	Sub-field	Number of papers			Average citations per paper		
		1999–2002	2003–2006	1999–2006	1999–2002	2003–2006	1999–2006
1	Artificial intelligence	374	829	1,203	3.39	2.97	3.10
2	Computer software	774	1,932	2,706	3.02	2.95	2.97
3	Cryptology	7	63	70	4.00	2.81	2.90
4	Database management systems	100	220	320	2.72	2.75	2.74
5	Internet and multi media	134	513	647	4.6	2.22	2.72
6	Computer networks	433	1,427	1,860	2.96	2.04	2.25
7	Software engineering	74	160	234	2.16	2.16	2.16
8	Computer architecture	61	144	205	1.65	2.30	2.11
9	Computer hardware	135	288	423	1.39	2.36	2.05
10	Computer theory	77	229	306	1.75	1.78	1.77
11	Operating systems	21	71	92	1.57	1.83	1.77

These 30 institutions together have contributed 11,487 papers, with an average number of papers per institution as 382.9. Nine institutions out of top 30 have contributed more than the average productivity (383 papers) of these total institutions. These institutions are Indian Institute of Science, Bangalore with 1,241 papers), followed by Indian Institute of Technology, Delhi (1,175 papers), Indian Institute of Technology, Kharagpur (1,050 papers), Indian Institute of Technology, Bombay (944 papers), Indian Institute of Technology, Madras (938 papers), Indian Statistical Institute, Kolkata (772 papers), Indian Institute of Technology, Kanpur (683 papers), Anna University, Chennai (502 papers) and International Business Machines (454 papers) (Table 10).

The 11,487 papers contributed by these 30 institutions together have received 17,105 citations, with average citations per paper as 1.49. The average citations per paper of these 30 institutions vary from 0.41 to 3.11. Nine institutions have registered higher average citations per paper than the average citations per paper (1.49) of 30 institutions. The maximum average citation per paper (3.11) is registered Bell Lab Research Centre India, followed by Indian Institute of Management, Kolkata (2.50), Indian Statistical Institute, Kolkata (2.47), Institute of Mathematical Sciences, Chennai (2.37), Indian Institute of Science, Bangalore (2.06), International Business Machines (2.02), Indian Institute of Technology, Kanpur (1.95), Indian Institute of Technology, New Delhi (1.82) and Netaji Subhas Institute of Technology, Delhi (1.50) (Table 9).

The h-index of these top 30 institutions varies from 4 to 35, with average h-index per institution as 13.3. Ten institutions have registered higher h-index than the h-index of all 30 institutions (13.3). The highest h-index (35) is registered by Indian Institute of Science, Bangalore, followed by Indian Statistical Institute, Kolkata (32), Indian Institute of Technology, New Delhi (30), Indian Institute of Technology, Kharagpur (25), Indian Institute of Technology, Bombay (23), Indian Institute of Technology, Kanpur (21), Indian Institute of Technology, Madras (20), International Business Machines (19), Bell Lab Research Centre (17) and Jadavpur University (16) (Table 10).

The international collaborative papers share of these 30 institutions varies from 1.24 to 68.33%, with the average share of international collaborative papers as 21.51%. Ten

Table 10 Research output, impact, international collaborative papers share and h-index of top institutions of India in computer science during 1999–2008

S.No	Name of institution	TP	TC	ACPP	H-Index	ICP	% ICP
1	Indian Institute of Science (IISc), Banglore	1,241	2,554	2.06	35	256	20.63
2	Indian Institute of Technology (IIT), Delhi	1,175	2,139	1.82	30	272	23.15
3	Indian Institute of Technology (IIT), Kharagpur	1,050	1,256	1.20	25	179	17.05
4	Indian Institute of Technology (IIT), Bombay	944	1,303	1.38	23	231	24.47
5	Indian Institute of Technology (IIT), Madras	938	1,229	1.31	20	186	19.83
6	Indian Statistical Institute (ISI), Kolkata	772	1,910	2.47	32	177	22.93
7	Indian Institute of Technology (IIT), Kanpur	683	1,333	1.95	21	182	26.65
8	Anna University, Chennai	502	315	0.63	9	38	7.57
9	International Business Machines	454	915	2.02	19	195	42.95
10	Jadavpur University, Kolkata	380	490	1.29	16	72	18.95
11	University of Delhi	359	369	1.03	11	53	14.76
12	Indian Institute of Technology (IIT), Roorkee	327	234	0.72	7	44	13.46
13	Indian Institute of Technology (IIT), Guwahati	291	255	0.88	11	43	14.78
14	University of Hyderabad	273	166	0.61	8	39	14.29
15	University of Calcutta	248	362	1.46	13	40	16.13
16	International Institute of Information Technology, Hyderabad	204	236	1.16	8	48	23.53
17	PSG College of Technology, Coimbatore	157	71	0.45	6	5	3.18
18	Birla Institute of Technology and Science, Pilani	136	109	0.80	8	24	17.65
19	Microsoft	128	117	0.91	5	44	34.38
20	Tata Institute of Fundamental Research, Mumbai	124	154	1.24	8	68	1.24
21	Institute of Mathematical Sciences, Chennai	122	289	2.37	13	53	2.37
22	Bell Labs Research Center, India	120	373	3.11	17	82	68.33
23	Indian Institute of Management (IIM), Kolkata	113	282	2.50	9	43	38.05
24	Netaji Subhas Institute of Technology, Delhi	113	169	1.50	8	9	7.96
25	Pondicherry Engineering College	113	46	0.41	5	3	2.65
26	Tata Consultancy Services India	110	58	0.53	5	19	17.27
27	University of Mysore	107	145	1.36	10	15	14.02
28	Banaras Hindu University, Varanasi	107	88	0.82	7	11	10.28
29	Aligarh Muslim University	100	90	0.90	6	32	32.00
30	National Institute of Technology, Tiruchirappalli	96	48	0.50	4	8	8.33

TP total papers, *TC* total citations, *ACPP* average citations per paper, *ICP* international collaborative papers

institutions have registered higher share of international collaborative papers than the average share of international collaborative papers of all 30 institutions. The maximum share (68.33%) of international collaborative papers is registered by Bell Lab Research Centre, followed by International Buisness Machines (42.95%), Indian Institute of Management, Kolkata (38.05%), Microsoft (34.38%), Aligarh Muslim University (32.00%), Indian Institute of Technology, Kanpur (26.65%), Indian Institute of Technology, Bombay (24.47%), Indian Institute of Information Technology, Hyderabad (23.53%), Indian Institute of Technology, Delhi (23.15%) and Indian Statistical Institute, Kolkata (22.93%) (Table 10).

Prolific authors in Indian computer science

Considering the contribution and impact prominent authors in computer science research in India, 16 Indian authors are identified as productive ones who have published more than 35 papers during 1999–2008. Of these 22 authors, five are affiliated with Indian Statistical Institute, Kolkata, followed by three each with Indian Institute of Science, Bangalore and Indian Institute of Technology, Mumbai, two each with Indian Institute of Technology, New Delhi and Indian Institute of Information Technology, Hyderabad and one each with Indian Institute of Technology, Kanpur, Indian Institute of Technology, Kharagpur, Defence Institute of Advanced Technology, Pune, PSG College of Technology, Coimbatore, Jadavpur University, Kolkata, University of Mysore and Visvesvaraya College of Engineering, Bangalore (Table 11).

These 22 authors together contributed 1,123 papers (7.05% share) in cumulative publication output of India, with an average of 51.04 papers per author. The publication productivity of these authors varies from 36 papers to 81 papers. Only ten authors have published higher papers than the group average (1.04 papers per author). These are Sankar Kumar Pal with 81 papers during 1999–2008, followed by Kalyanmoy Deb (79 papers), Lalit Mohan Patnaik (63 papers), Nikhil R. Pal (61 papers), Sanghamitra Bandyopadhyay (58 papers), Palash Sarkar (57 papers), Bayya Yegnanarayana (56 papers), S.N. Sivanandam (56 papers), Subhasis Chaudhuri (54 papers) and Amit Ferit Konar (52 papers) (Table 11).

These authors have together received the average of 2.57 citations per paper for the total papers published by these authors during 1999–2008, and it varies from 0.32 to 7.20. Seven authors have scored higher citations than the average of 5.44 citations per paper. These are R.K. Mallik with average citation per paper of 9.90, followed by K. Deb (7.20), N.R. Pal (4.98), S.K. Pal (4.42), S. Bandyopadhyay (3.64), S. Chaudhuri (3.04) and K. Ramamritham (2.63) (Table 11).

The average h-index value of these authors is 7.86 during 1999–2008 and it varies from 2 to 17. Nine authors registered higher h-index value than group average are R. Mallik with h-index of 17, followed by K. Deb (16), S.K. Pal (14), N.R. Pal (14), S. Bandhyopadhyay (13), K. Ramamritham (11), B.B. Chaudhuri (10), S. Chaudhuri (9) and P. Sarkar (8) (Table 11).

The average share of international collaborative papers of these 22 authors is 19.70% and it varies from 2.53 to 35.44%. Five authors have registered higher than the average share of international collaborative papers. These are K. Ramamritham with 35.44% share, followed by A.F. Konar and K. Deb (30.38% share), N.R. Pal (21.52% share) and R.K. Mallik (18.99% share).

Research communication in high productive journals

The top 35 most productive Indian and foreign Journals contributing to Indian computer science output together contributed 27.10% share in the cumulative publication output of Indian in computer science during 1999–2008. The cumulative share of these 35 journals showed decrease from 37.13% in 1999–2003 to 24.09% in 2004–2008 (Table 12).

Research patterns of high cited papers

The characteristics of top 100 most high-cited papers of India in computer science were also evaluated in this section, based on data given in Table 13 (see Supplementary

Table 11 Research output, impact and h-index of top productive authors of India in computer science, 1999–2008

S.No.	Name	Affiliation	TP	TC	ACPPP	h-index	ICP	% ICP
1	Kalyanmoy Deb	Indian Inst. of Techn., Dept. of Mech. Engn., Kanpur	79	569	7.20	16	24	30.38
2	Sankar Kumar Pal	Indian Stat. Inst., Ctr. for Soft Computing Res., Kolkata	81	358	4.42	14	10	12.66
3	Lalit Mohan Patnaik	Defence Institute of Advanced Technology, Pune	63	61	0.97	6	3	3.797
4	Nikhil R. Pal	Indian Stat. Inst., Electr. and Comm. Scie. Unit, Calcutta	61	304	4.98	14	17	21.52
5	Sanghamitra Bandyopadhyay	Indian Stat. Inst., Machine Intelligence Unit, Kolkata	58	211	3.64	13	4	5.06
6	Palash Sarkar	Indian Stat. Inst., Applied Statistics Unit, Kolkata	57	101	1.77	8	13	16.46
7	Bayya Yegnanarayana	Int. Inst. of Information Technology, Hyderabad	56	79	1.41	7	12	15.19
8	S. N. Sivanandam	PSG College of Technology, Dept. of Comp. Sci. and Engn., Coimbatore	56	20	0.36	4	1	1.28
9	Subhasis Chaudhuri	Indian Inst. of Tech., Dept. of Electrical Engn., Mumbai	54	164	3.04	9	14	17.72
10	Amit Ferit Konar	Jadavpur Univ., Dept. of Electron. and Telecom. Engn., Kolkata	52	25	0.48	5	24	30.38
11	C. V. Jawahar	Int. Inst. of Information Tech., Ctr. for Visual Inform. Techn., Hyderabad	50	27	0.54	3	4	5.06
12	Krithi Ramamritham	Indian Inst. of Tech., Mumbai	49	129	2.63	11	28	35.44
13	Santanu Pal Chaudhury	Indian Inst. of Techn., Multimedia Laboratory, New Delhi	47	54	1.15	5	4	5.06
14	Bidyut Baran Chaudhuri	Indian Statistical Institue, Kolkata	43	99	2.3	10	10	12.66
15	K. Venugopal	Visvesvaraya Coll.of Engn., Dept.of Comp. Sci. and Engn., Bangalore	41	30	0.73	6	2	2.53
16	Utpal B. Desai	Indian Inst. of Techn., Dept. of Electr. Engn., Mumbai	41	45	1.1	6	5	6.33
17	Dillip S. Guru	Univ. of Mysore, Int. Sch. of Inform. Manag., Mysore	40	76	1.9	2	3	3.797
18	Thip. Sreenivas	Indian Inst. of Sci., Dept. of Electr. Comm. Engn., Bangalore	40	29	0.73	4	2	2.532
19	Partha Chakrabarti	Indian Institute of Technology, Kharagpur	43	54	1.26	4	5	6.329
20	Ranjan K. Mallik	Indian Inst. of Tech., Dept. of Electr. Engn., New Delhi	39	386	9.9	17	15	18.99
21	A. Ramakrishnan	Indian Inst. of Sci., Dept. Electr. Engn., Medi. Intelligence and Language Engn., Lab., Bangalore	37	12	0.32	4	2	2.532
22	Jayant R. Haritsa	Indian Inst. of Sci., Database Systems Lab., Bangalore	36	55	1.53	5	8	10.13

TP total papers, *TC* total citations, *ACPP* average citations per paper, *ICP* international collaborative papers

Table 12 List of highly productive journals publishing papers of India in computer science, 1999–2008

S.No.	Name of journal	Period		
		1999–2008	1999–2003	2004–2008
1	Lecture Notes in Computer Science Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics	1,437	122	1,315
2	IETE Journal of Research	408	235	173
3	Journal of Molecular Structure Theochem	270	109	161
4	Information Technology Journal	139	0	139
5	Pattern Recognition Journal	134	51	83
6	Modelling Measurement and Control B	122	37	85
7	Fuzzy Sets and Systems	118	84	34
8	Signal Processing	108	46	62
9	Pattern Recognition	103	54	49
10	Studies in Computational Intelligence	102	0	102
11	Applied Soft Computing Journal	80	5	75
12	Scientometrics	74	50	24
13	Computer Communications	71	34	37
14	Computers and Structures	68	46	22
15	Bioinformatics	67	23	44
16	Advances in Modelling and Analysis B	65	5	60
17	Information Sciences	64	18	46
18	International Journal of Numerical Methods in Fluids	61	24	37
19	IEEE Transactions on Information Theory	59	13	46
20	Information Processing Letters	58	31	27
21	Mathematical and Computer Modelling	56	0	56
22	Journal of Molecular Modeling	54	9	45
23	IEEE Transactions on Signal Processing	49	26	23
24	IEEE International Conference on Fuzzy Systems	48	25	23
25	IEEE Transactions on Antennas and Propagation	47	21	26
26	Finite Elements in Analysis and Design	47	16	31
27	Microelectronic Engineering	47	21	26
28	Neurocomputing	46	17	29
29	Journal of Computer Science	46	0	46
30	IEEE Trans. Systems Man and Cybernetics Part B	46	20	26
31	Advances in Modelling and Analysis C	46	0	0
32	International Journal of Modelling and Simulation	46	7	39
33	Computer Methods in Applied Mechanics and Engineering	44	21	23
34	International Journal of Systems Science	43	21	22
35	Journal of Institution of Engineers Part CP. Computer Engineering Division	42	40	2
	Total	4,315	1,231	3,038
	Total India's output	15,924	3,315	12,609
	Share of 35 journals in India's output	27.10	37.13	24.09

material).[1] Based on publications output of India in this area, 100 papers are identified as highly cited ones, who have received citations since their publications till 1 October 2009 from 45 to 1,880 during 1999–2009. Of these 100 papers, 91 appeared as articles, four as reviews, four as conference papers and one as letter. Of the 100 high-cited papers, 57 involve international collaboration (48 bilateral and nine multilateral) and 16 involve national collaboration (Table 13, see Supplementary material).

These 100 papers are in citations range of 48–1,880 and have together received 12,630 citations with an average of 126.3 citations per paper and the median of 71. Of these 100 papers, two papers are in citation range of 1,801–1,900, one papers in citations range of 301–400, four papers in citations range of 201–300, 21 papers in citation range of 101–200, 16 papers in citations range of 76–100, 46 papers in citations range of 51–75 and nine papers in citations range of 26–50. The authors of these high cited papers are affiliated to 52 Indian institutions including 17 papers from Indian Institute of Science, Bangalore, 16 papers from Indian Statistical Institute, Kolkata, 13 papers from Indian Institute of Technology, New Delhi, 12 papers from Indian Institute of Technology, Kanpur and six papers each from Indian Institute of Technology, Kharagpur and Indian Institute of Technology, Madras, four papers from Kalyani Government Engineering, three papers each from Institute of Microbial Technology, Chandigarh and Jadavpur University, Kolkata, two papers each from Birla Institute of Technology and Science, Pilani, Indian Institute of Management, Bangalore, Indian Institute of Management, Kolkata, Jamia Millia Islamia, Delhi and Tejas Networks, Bangalore, one paper each from 38 other Indian institutions (Table 12).

These 100 high cited papers have appeared in 48 journals, including seven in *Bioinformatics*, six each in *IEEE Transactions on Evolutionary Computation* and *IEEE Transactions on Information Theory*, four papers each in *IEEE Transactions on Neural Networks*, *IEEE Transactions on Fuzzy Sets*, *Evolutionary Computation* and *IEEE Journal on Selected Areas in Communication*, three papers each *in IEEE Networks, IEEE Software*, *IEEE Transactions on Communication, Pattern Recognition* and *Networks*, two papers each in *ACM Computing Surveys, Computer Networks*, *Fuzzy Sets and Systems*, *IEEE Communication Letters*, *IEEE Communication Magazine, IEEE Transactions on Consumer Electronics, IEEE Transactions on Image Processing*, *IEEE Transactions on Pattern Analysis and Machine Intelligence, IEEE Transactions on Systems, Man* and *Cybernetics, Part B: Cybernetics and IEEE/ACM Transactions on Networking*, and one papers each in 38 other journals (Table 12).

Summary and conclusion

India's published 15,924 papers in computer science during 1999–2008, compared to 126,140 papers by China, 32,711 papers by South Korea, 26,021 papers by Taiwan and 10,132 papers by Brazil. India ranks at 13th position among the top 24 countries in computer science, with its global publication share of 1.72% during 1999–2008. Compared to India, China, South Korea, Taiwan and Brazil ranks at 2nd, 8th, 10th and 17th position, with global publication share of 13.60, 3.53, 2.81 and 1.09% during 1999–2008. India witnessed rise in global publication share from 1.38% in 1999 to 2.23% in 2008, compared to China (from 3.80 to 21.83%), South Korea (from 2.37 to 3.18%), Taiwan (from 2.78 to

[1] Table 13. List of top 100 high cited papers in computer science from India. Available as supplement in electronic format of this paper.

3.1%) and Brazil (from 0.88 to 1.19%) during the same periods. Correspondingly, India's world ranking improved from 16th position in 1999 to 13th position in 2008, compared to China (from 7th to 1st), South Korea (from 10th to 9th), Taiwan (9th to 8th) and Brazil (from 20th to 16th). India's annual average publication growth rate in computer science during 1999–2008 was 20.37%, compared to 47.92% for China, 25.92% for South Korea, 25.75% for Brazil and 22.94% for Taiwan.

In terms of impact and quality, the average citation per paper registered by India's publication output in computer science during 1999–2006 was 2.10. The average citations per paper for India's cumulative publications decreased from 2.31 during 1999–2002 to 2.01 during 2003–2006 (Table 2). The h-index registered by all Indian papers in computer science during 1999–2008 was 60.

The cumulative international collaborative publication output of India contributed 19.92% share in the total cumulative output of India in computer science during 1999–2008, compared to 10.42% by China, 15.99% by South Korea, 11.33% by Taiwan and 28.10% by Brazil during the same period. Both India and China have shown decrease in its share of internationally collaborative papers from 24.95 and 12.69% during 1999–2003 to 18.60 and 10.15% during 2004–2008, compared to increase in internationally collaborative papers of South Korea, Taiwan and Brazil from 14.59, 10.21 and 25.75% during 1999–2003 to 16.39, 11.73 and 29.15% during 2004–2008.

Among the collaborative countries, USA is the major collaborator with India during 1999–2008 with 47.70% share, followed by United Kingdom (8.62% share), Canada, Germany, Singapore, France and Japan (between 5.34 and 7.72% share), Australia, South Korea, and Italy (between 3.73 and 4.30%), Malaysia, China and Switzerland (between 2 and 3%), and Netherlands, Norway, Georgia, Taiwan, Spain, Sweden, Israel, Finland, Belgium, Denmark and Mexico (between 1 and 1.8%). It was observed that the share of United States have decreased by 17.98% from 1999–2003 to 2004–2008, followed by Netherlands (0.67%), Germany (0.43%), Singapore (0.18%), Israel (0.18%), Denmark (0.18%), Japan (0.14%) and China (0.07%), while the share of all other major collaborating countries have increased by 2.70% in Australia, followed by South Korea (2.36%), Norway (2.27%), France (2.14%), UK (1.52%), Italy (1.44%), Finland (1.09%), Canada (0.86%), Georgia (0.64%) and Poland (0.51%).

Among the major sub-fields in Indian computer science research during 1999–2008, the maximum research priority (30.43% share) is assigned to computer software, followed by computer networks (24.91% share), artificial intelligence (15.03% share), cryptology and computer hardware (4.53% share each), database management system (3.41% share), software engineering (3.24% share), computer theory (3.17% share), internet and multimedia (3.13% share), computer architecture (1.78% share) and operating systems (1.06% share). This trend is the same in other countries such as China, South Korea, Taiwan and Brazil.

The cumulative publication output of 30 most productive institutions in India's total research output in computer science during 1999–2008 was 11,487 papers (72.14% of the India's total output in this field), with an average number of papers per institution as 382.9. The average citations per paper of these 30 institutions vary from 0.41 to 3.11, with an average impact of 1.49 citations per paper during 1999–2008. The h-index of these top 30 institutions varies from 4 to 35, with average h-index per institution as 13.3 and an average h-index value of 13.3 during 1999–2008. The international collaborative papers share of these 30 institutions varies from 1.24 to 68.33%, with the average share of international collaborative papers as 21.51% during 1999–2008.

The 22 most productive Indian authors in computer science field together contributed 1,123 papers (contributing 7.05% share in cumulative publication output of India during 1999–2008), with an average of 51.04 papers per author. The average citations per paper of these 22 authors vary from 0.32 to 7.20, with an average impact of 2.57 citations per paper during 1999–2008. The h-index of these 22 authors varies from 2 to 17, with average h-index per author as 7.86 during 1999–2008. The international collaborative papers share of these 22 authors varies from 2.53 to 35.44%, with the average share of international collaborative papers as 19.70% during 1999–2008.

The total publication output of top 35 most productive journals in computer science together contributed 27.10% share to the total publication output of India in computer science during 1999–2008. The cumulative share of these 35 journals showed decrease from 37.13% in 1999–2003 to 24.09% in 2004–2008.

Based on publications output of India in this area, 100 papers are identified as highly cited ones, who have received citations since their publications till 1 October 2009 from 45 to 1,880 during 1999–2009. These 100 papers are in citations range of 48–1,880 and have together received 12,630 citations with an average of 126.3 citations per paper and a median of 71. Of these 100 papers, two papers are in citation range of 1,801–1,900, one papers in citations range of 301–400, four papers in citations range of 201–300, 21 papers in citation range of 101–200, 16 papers in citations range of 76–100, 46 papers in citations range of 51–75 and nine papers in citations range of 26–50. Of the 100 high-cited papers, 57 involve international collaboration (48 bilateral and nine multilateral) and 16 involve national collaboration. The authors of these high-cited papers are affiliated to 52 Indian institutions including 17 papers from Indian Institute of Science, Bangalore, 16 papers from Indian Statistical Institute, Kolkata, 13 papers from Indian Institute of Technology, New Delhi, 12 papers from Indian Institute of Technology, Kanpur, etc. These 100 high cited papers have appeared in 48 journals, including seven in *Bioinformatics*, six each in *IEEE Transactions on Evolutionary Computation* and *IEEE Transactions on Information Theory*, four papers each in *IEEE Transactions on Neural Networks*, *IEEE Transactions on Fuzzy Sets, Evolutionary Computation* and *IEEE Journal on Selected Areas in Communication*, etc.

India is far behind China, South Korea, Taiwan and Brazil in terms of publication output, citation quality and share of international quality in computer science. It means, substantial increase in R&D investments, development of new training programs and manpower deployment from the government are required in this area. National and international collaboration has to be been substantially increased to improve more quality and publication output.

In today's knowledge economy, new products and services developed through R&D are going to be amongst the most significant contributors to future GDP growth. R&D research in ICT is of critical importance for the nations security and for fulfilling various societal objectives. At present India's investment in ICT sector is very low compared to many other countries. The government must review and reverse its R&D policies to encourage mush higher level of investment in R&D. The R&D projects must encourage collaboration and outsourcing to leverage on external advice. The public–private partnership for development and commercialization of technology should be encouraged.

There is a shortage of qualified manpower (students with PhD degrees) in India for undertaking research in Indian academic, R&D centers and in industry. Hardly 40–50 PhD's are produced in ICT area each year in India. With a view to attract students to go for PhD degree, The Ministry of Information Technology should institute create a number of prestigious research fellowships at enhanced rates, with provisions for participations in

international conferences/seminars. At present a large proportion of R&D funds in ICT area is given to few bigger academic and research institutions. Since India has a vast infrastructure of different type of institutions, therefore R&D funding should be widely distributed across all type of institutions both in terms of smaller and bigger projects. In addition, the Ministry of Information Technology should set up centers of excellence at premier academic and research institutions involving multi faculty members with different specializations.

Thrust areas in ICT for R&D and technology development should be identified and R&D projects should focus for achievable under these thrust areas. The government must review its thrust areas on regular basis, remove such areas that are stabilized, and induct new ones that need to be supported. Even in respect of cutting and emerging areas, the government has to make forward farsighted allocation of resources as these build strong national capability in ICT areas.

Appendix 1

Keywords used or searching publication data on the following sub-fields.

Computation theory

Finite automata, regular and language or expression, context-free) and (grammar or language), recursive function, turing machine, time complexity, automata theory, computation theory.

Software engineering

Software and engineering, object-oriented design, black box and white box and testing), incremental testing, software metrics, software reliability, software standard, cocomo, capability maturity model, petri net, srs or uml.

Database management systems

"Database management system, data abstraction, data definition language" or "ddl, data dictionary, e-r diagram, relational database management system" or rdbms, query language, sql" or odl or oql, relational calculus, bi-relation or multi relation, join algorithm, shadow paging, data ware house, data structure, data manupulation language or dml, database task group or dbtg.

Internet and multimedia

Internet programming, html, xml, applete programming, http*, web server, search engine, crawler technology, internet robot, web mining, e-commerce, web security, user interface style, visual design, multimedia, ip address, firewall, internet.

Artificial intelligence

Artificial intelligence, production system and matching, problem reduction, search space, heuristic search, knowledge representation, semantic net, fuzzy and (reasoning or logic),

neural and (network or language), pattern directed search, propositional and predicate logic, natural language understanding, vision understanding, speech understanding, genetic algorithm.

Computer networks

Network and protocol, wireless and (comm* or network), bandwidth and data, local area network or LAN, router, congestion and control, inter and connection and network, computer and network), Asynchronous and transfer and (mode or switch), client and server and (system or comput*), wide area network″ or WAN, broadband), packet and switch*, socket and switch*, optical and connection, gateway* and computer and network), data transfer, distributed computing, world wide web″ or WWW, packet OR circuit) and switch*, Internet and protocol, proxy and server, TCP-IP.

Computer software

Computer AND software, computer simulation, computer aided″ AND (software OR design), compiler design, object oriented program*, real time system, data mining, data acquisition, pattern and (matching OR recognition), image processing, java programming, programming language, software and architecture, software and (design or engineering or testing), user computer interface, computer graphic, graph theory.

Computer architecture

Computer architecture, (cisc or risc) and architecture, sisd, simd, misd, mimd, instruction pipelining, cache memory, virtual memory, interleaved memory, shared-memory and architecture, computer organi*, instruction format, addressing mode.

Operating system

Operating system, interrupt handling, batch-processing, multiprogramming, demand paging, cpu scheduling, concurrent process, deadlock and (prevention or avoidance or detection or recovery), spool management, directory structure, file system, multiprocessing.

Cryptology

Cryptography and cryptanalysis, (private or public) and cryptography, linear cryptanalysis, rsa system, digital signature, stream ciphers.

Computer hardware

Computer and hardware, digital signal processing, computer architecture, cmos.

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