Research and Innovation Capabilities : Insights on India's plunge into Nanotechnology

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1. Introduction

Nanotechnology is expected to be one of the main drivers of future industries' development and economic growth (see, for instance, Huang et al., 2004; Hullmann, 2007; Kostoff et al., 2007; Meyer et al., 2008; Salerno et al., 2008 ; Roco et al., 2010). Nanotechnology's significant potential for technological change and for current and future world markets becomes apparent when looking at its market size and its growth potential. Estimates by market research and industry analysis show that the market for the nanotechnology was 11.67 billion US$ in 2009 and is expected to grow at a CAGR of around 17.5% during 2016-2022 (BCC, 2010; RNCOS, 2015).

The promise of the socio-economic benefits that could be derived from nanotechnology has resulted in both developed and developing country investment and R&D engagement with nanotechnology, as the UNESCO Science Report: Towards 2030 explains. Indeed, the USA formally marked the start of an international technology race in nanotechnology, with the launching of its 'National Nanotechnology Initiative' in January 2000, consecrating the phenomenal amount of US$270 million to this promising field. The rest of the world has followed suite with minimal delay – presumably to avoid the technological lag. The EU Framework Program for Research and Technological Development in Europe made it one of its themes in the 5th Framework Programme (1998–2002), with an overall budget of €14.96 billion. Developing and transition economies of Brazil, Russia, India, China, and South Africa (BRICS) have also given nanotechnology a high priority, and all countries have defined a national plan for its development. Brazil, India, and China already account for more than 1 per cent each of the world's total investment in nanotechnology, which is expected to grow further (Aguirre-Bastos, 2010).

However, the capabilities to realize the actual application potential of advancements in science and technolology would vary given the interactive and context-dependent nature of innovation in general (Lundvall, 1992), and the greater degree of complexity and potential impacts that could be experienced and would need to be managed in engaging with this emerging technology. Further, the international economic crisis have affected research and innovation policies and activities, the impacts of which differed substantially across countries, types of businesses and types of innovation (OECD, 2012).

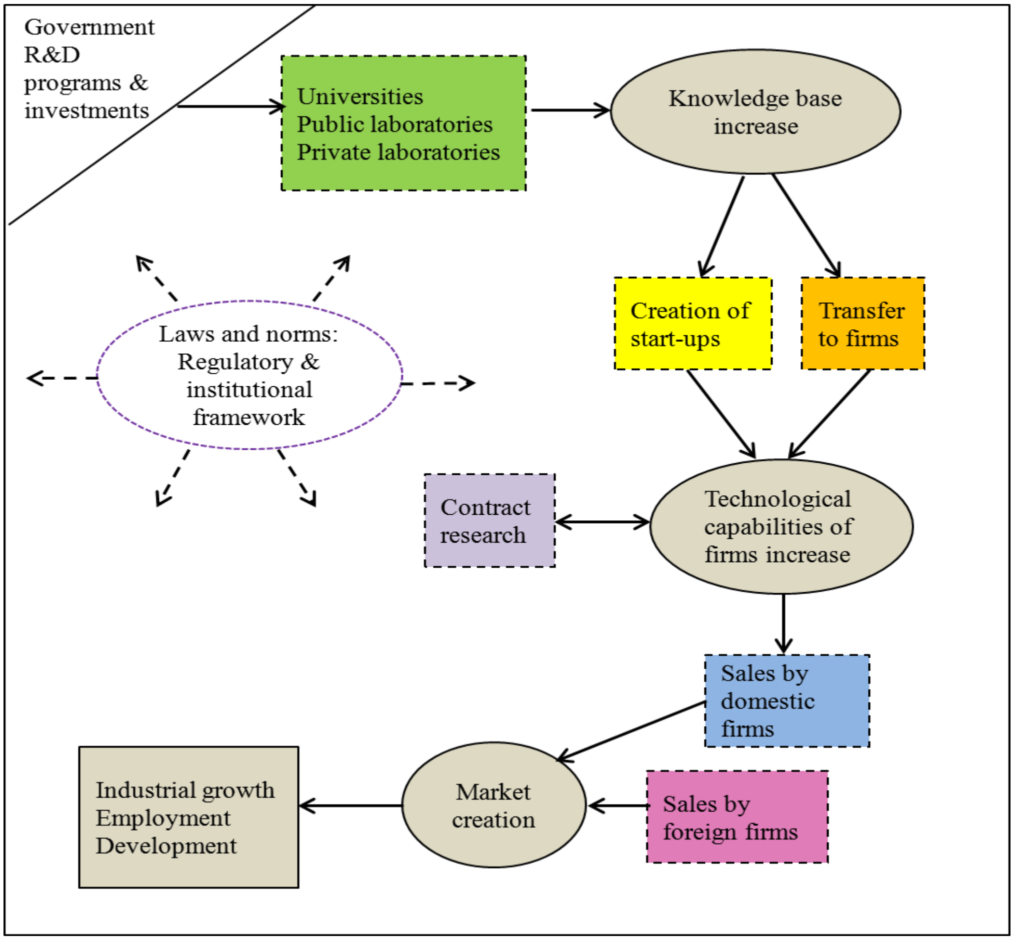
Given its potential for economic growth and development, India with its established scientific capabilities has every incentive to carve out a niche in nanotechnology. Are we on the right trajectory of nanotechnology development ? Accordingly, the paper attempts to understand nanotechnology developments and reflect on research and innovation capability in the context of nanotechnology in India. First, the constituents of the conceptual framework are introduced and discussed. In the subsequent sections, an exploration of nanotechnology research and innovation capacity buiilding trajectory is undertaken. An investigation of the extent and trend of nanotechnology development in India scoping the actors, infrastructure, development of human and financial resources, the public policies bearing on nanotech research and innovative activity, business sophistication is made.

For mapping main events and key actors, a variety of sources related to nanotechnology development and diffusion was retrieved. The data set encompassed articles published in journals, official statistics, reports from industry associations, research organizations, etc. and news items from newspapers, government and company websites, etc. The data were used to undertsand the evolution of trajectory of nanotechnology in India. Further, interactions with wide range of stakeholders in India from the academia, research laboratories, industry, policy making, civil society, and the media was undertaken. An attempt has been made to provide an explanatory account of the capacity building, documented by the data on publications and patents.

2. Framework

In an emerging technology different capabilities are supported and mobilized by a variety of actors, networks, and institutions during the often extensive lead time from idea generation to market offering. Key competences might be missing, networks are often weak or non-existing, and the institutional set-up is usually not properly aligned with the emerging technology. **Figure 1** illustrates the essence of the capacity building process marking the emergence of the research and innovation activities in an emerging technology.

Figure 1: Trajectory for capacity building in emerging technology



Source: Author

Positive expectations about a technology may lead to government R&D programmes and investments in an emerging technology. The competence level in the existing knowledge domains can act as a stimulus for engaging with emerging technologies. Firms and start-ups foreseeing the opportunities for commercial or societal gain of an emerging technology may engage with it and can benefit from the research and knowledge base. Subsequently, development of marketing strategies by these firms (domestic as well as foreign) may further lead to increase in demand for the emerging technology. Various factors such as policies, human resources, infrastructure, market conditions, and business practices would influence the performance of these activities. Policy also has an important role in facilitating linkages among organizations, improving information flow, and exchange between private and public sectors and strengthening institutions that facilitate innovation.

Capability building is a dynamic process comprising of several actors and interactive learning and it is important that research and innovation activities are relevant to the market. In this regard, the capability framework has to be viewed both as a system and process. It is a system since the existence of inter-linkages and knowledge flow among the heterogeneous set of elements would be crucial. Further, building capability is a continuous process as there are always opportunities and demands on the anvil, thus requiring a constant redefinition of strategies and policies on the part of various actors to engage with them.

3. Research capabilities

Science and technology (S&T) infrastructure in India currently encompasses more than 730 universities, 1848 research laboratories, 74 institutes of national importance, and 3324 in-house industrial R&D units, besides several other government departments, private, international and non-profitable organizations.

In the Indian S&T system, teaching and research are more or less delinked. Research institutes were created to perform research independent of the university system, and the universities had the primary mandate of teaching. Main categories of universities in India are – Central Universities, State Universities, Deemed-to-be Universities and Private Universities. The central universities are small in number with some of them having made their mark in the research scenario. Among the state universities, which constitute the largest chunk of the university system, few were doing respectable research and the need for strengthening their quality of education and research has been widely felt (Datta & Saad, 2011). Some of the deemed-to-be-universities are high performing research institutes, the most important being the Indian Institute of Science Bangalore (IISc). Institutes of National Importance are largely constituted of the IITs (Indian Institute of Technology), NITs (National Institute of Technology), and IISERs (Indian Institutes of

Science Education and Research). The IITs and NITs have been established primarily to conduct professional courses in engineering. In addition to education, these institutes also undertake research in science and technology. The IISERs are the latest entrants in the S&T research system and are intended to be the IITs of basic sciences. **Table 1** provides the organization profile of the S&T system in India in terms of their facts and performances.

Table 1: Indian S&T system – facts and performance

Category	**No. of institute**	**No. of institute in the top 30 publishing institutes in India**	**Total SCI papers of institutes in the top 30 category (2009-2014)**	**Top publishing institute – Total papers (% share){Citations} [Citations per paper] (2009-2014)**	**Subject area publication counts of top publishing institutes**
Central Universities	40	5	28,264	University of Delhi 9,272 (1.70){60,689}[6.55]	Physics & Astronomy (2296) Medicine (1785)
State Universities	342	10	44,339	Anna University 9,198 (1.68){26,040}[2.83]	Engineering (3765) Computer Science (3197)
Deemed Universities	125	6	36,041	IISc. Bangalore 12,310 (2.26){84,716}[6.88]	Physics & Astronomy (3700) Engineering (3641)
Private Universities	228	0	0	-	-
Institutes of National Importance	74	8	52,795	IIT Kharagpur 9,378 (1.72){54,862}[5.85]	Engineering (3645) Materials Science (2458)

Source: Compiled by the author based on data from DST website (http://www.nstmis-dst.org) and Ministry of Human Resource Development, Government of India website (www.mhrd.gov.in)

A large network of research organizations for advanced research outside the university system was set up in India. The three apex bodies are the Indian Council of Medical Research (ICMR), established in 1911 and having 32 laboratories, the Indian Council of Agricultural Research (ICAR), established in 1929 and having 99 institutes and 17 research centres, and the Council of Scientific, and Industrial Research (CSIR), established in 1942 and having 38 laboratories. Defense Research Development Organization (DRDO), formed in 1958 having 48 laboratories and the Department of Atomic Energy (DAE) were also established to increase the scientific base. There are many other publicly funded organizations that perform R&D for industries related to steel, renewable energy, oil and natural gas, coal, textiles, road transport, railways, electronics and communication, environment and forests, irrigation, and so on. There are also more than 1200 state or privately-funded Scientific and Industrial Research Organizations (SIROs).

The research institutes and laboratories in India depended on universities and colleges for meeting its S&T personnel requirement. Of late many of the research institutes and laboratories started their Ph.D. and Post Graduate research training programmes, largely due to lack of availability of manpower as per the requirements. This has also led to a dilution of the original objectives of these laboratories and institutes. For example, CSIRs original mandate was to act as a bridge between the academic and industrial worlds, but its laboratories began to supervise students for Ph.D. degree, conduct examinations for Ph.D. admissions and publications.

Similarly, strategic sectors like atomic energy, space, and defence started its training centres and institutes for generating human resources in their respective research domains. Department of Atomic Energy actually formed a university structure, a deemed university to give a degree and to create its resources. Department of Atomic Energy has also created its own system through Bhabha School. Department of Space has also created its training centres at the university and DRDO has similarly formed their own resources.

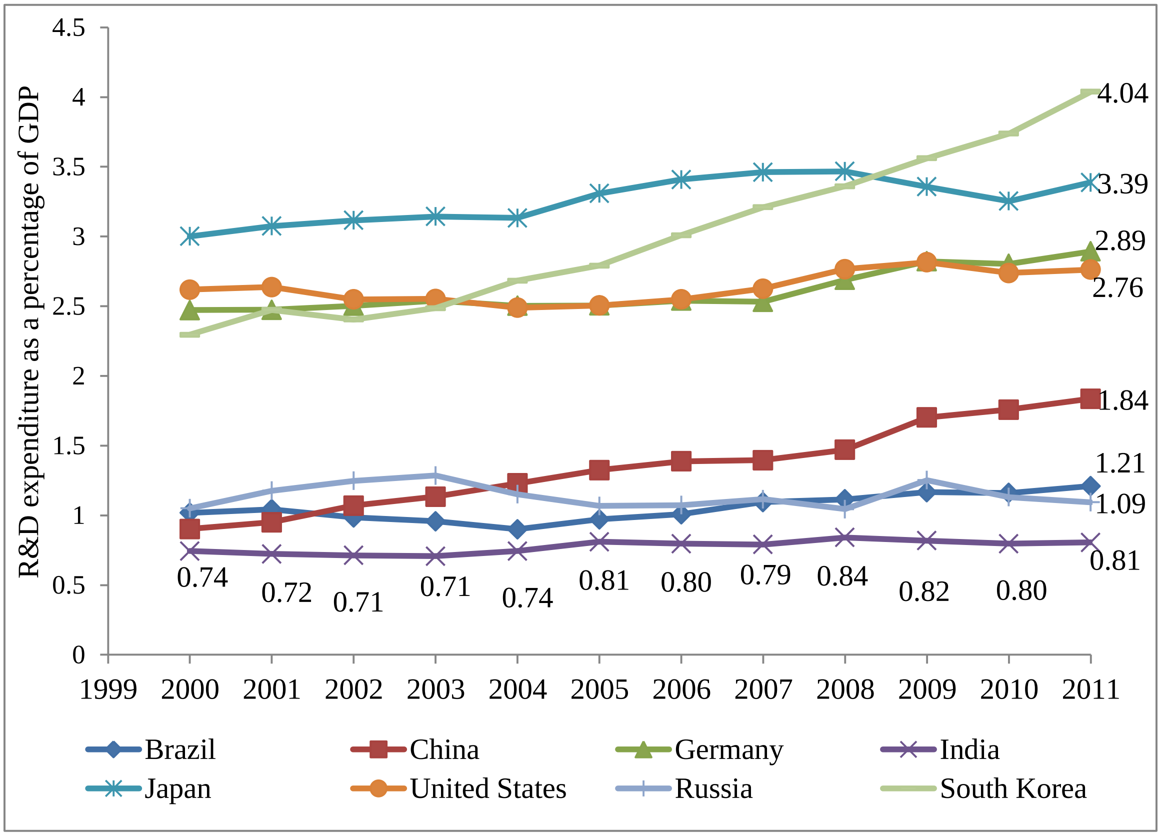
To keep pace with other countries in producing more Ph.Ds in the field of integrative and inter-disciplinary areas of science and engineering The Academy of Scientific and Innovative Research (AcSIR) has been established by Parliament's Academy of Scientific Innovative Research Act, 2011. Both Master's degree programmes and Ph.D. programmes will be run here, and it will train around 1,000 students a year who will be allowed to use all the 38 CSIR laboratories. The focus will be on imparting instruction in areas that are not normally taught in regular academic set up in India.

Further, the separation of education and research activities in Indian universities has been compounded by the lack of collaboration between different departments in universities and research institutes.

One of the major limitations with the Indian S&T system, compared to other emerging nations and the international context, is the very low level of gross expenditure on R&D. From the perspective of overall budgetary provisions, the major challenge is to implement the research policy commitments of spending 2% of GDP on R&D, up from 0.88% in 2011-12 (DST, 2013). Although investment in S&T has been increasing from INR 3974.17 crore in 1990-91 to INR 72620.44 (estimated) in 2011-12, it has not been able to keep up with the national GDP. The Government still fund around 2/3rd of the funding; it has not been very effective in introducing private enterprises to invest in R&D although there has been an increase in the proportion of business enterprise sector R&D from 18% in 2001-02 to 30% in 2011-12. Of the total R&D expenditure by major Indian scientific agencies, a sizeable chunk of around 61% is cornered by strategic sectors, i.e., defence, atomic energy, and space leaving a somewhat deficient share for the civilian S&T in which the ICAR and CSIR are the largest recipients. **Figures 2** and **3** provide some key R&D related statistics of India vis-à-vis some other countries of the world.

With regard to breakdown of government expenditure on R&D by type of research, the relative share of applied research and basic research to total R&D expenditure declined from around 38% and 28% respectively in 2003 to 36% and 26% respectively in 2010 whereas, the share of experimental development to total R&D expenditure witnessed an increase from 34% in 2003 to 38% in 2010 (DST, 2013). Also, there has been a gradual change in the R&D scenario with the focus of the government shifting towards commercially-oriented R&D. A major perceptible change in government R&D is that the mission-oriented projects are replacing open-ended research programs. The Twelfth Plan (2012-17) calls for launching mission mode projects addressing national needs and priorities in the areas of health, water, energy, food and environment security through the extensive participation of stakeholders.

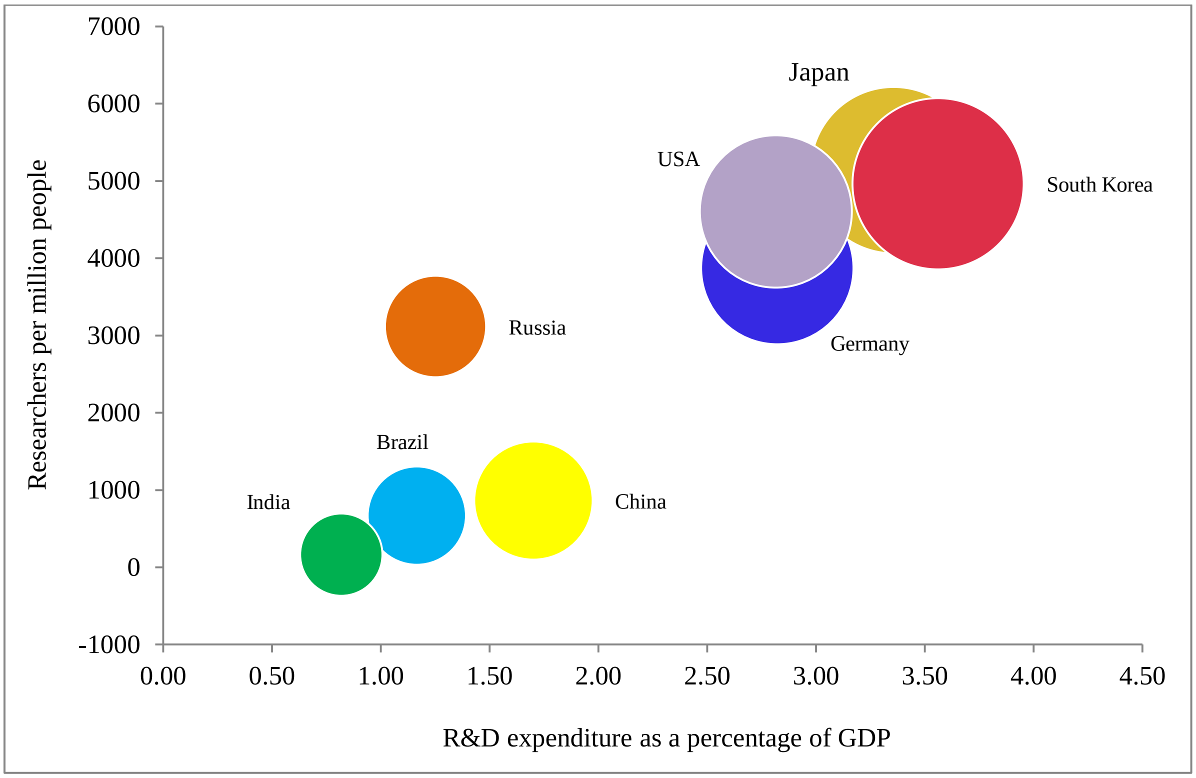
Figure 2: Percentage of GDP spent on R&D in BRICK and other countries, 2000-11



Source: Author's elaboration based on data from World Development Indicators, World Bank

In terms of research output and research collaborations, as per Thomson Reuters data, India's research publication shows a steep rise, especially since 2003 and its share of global scientific publication is 4.4% in 2013. In 2013, 16.0% of India's publication was the result of international collaboration, 32.1% the result of national collaboration, 46.2% the result of organizational collaboration, and 5.7% are single-authored papers. Collaborations with the USA are the most numerous, however; India's most impactful collaborations are not necessarily with the most impactful countries, but rather those with emergent countries across the globe. Also, greater collaboration with Asian countries has been seen. It could be argued that in order to further increase the impact of India's internationally collaborated research, it may be more selective in its most prolific collaborations.

Figure 3: R&D expenditure (percentage of GDP) and S&T human resources (per million people) of BRICK and other countries, 2009



Note: Size of circle reflects the relative amount of annual R&D spending by the country

Source: Author's elaboration based on data on R&D expenditure from World Development Indicators, World Bank and data on S&T human resources from UNESCO

Research publication focus of India demonstrates its strength in the basic sciences such as chemistry, physics, pharmacology and toxicology. India's publication activities in disciplines like microbiology, pharmacology, and material science seem to have maintained high growth rates. Over the years India has developed significant capabilities in diversified areas such as ICT (software and hardware), life sciences (including biotechnology, pharmaceuticals and bioinformatics), space technology, aviation, nuclear and other energy technologies, agricultural, chemical and materials sciences and emerging capabilities in automotive research and telecommunications (Mitra, 2007). Human resources, skills and the vast organizational base already created in the higher educational system have all contributed towards much of this dynamism witnessed in the knowledge-based and high technology sectors of the Indian economy.

Following trends are discernible from the above account of Indian S&T system. First, over the years India has built up a relatively substantial S&T infrastructure. India's innovation system is dominated by public research systems including institutes of higher education. The majority of higher education establishments focus on teaching (most of the universities; exceptions are the IISERs, the IITs, the All India Institutes of Medical Sciences (AIIMS), the Indian Institute of Science, the Tata Institute of Fundamental Research and around 20 major central universities), although the government acknowledges that scientific research should be an integral activity of the universities with greater focus on research leading to a doctorate degree without which quality teaching is not sustainable.[1]

Second, there is government's direct involvement in R&D which poses challenges in terms of emphasizing procedures over results, inappropriate choice of policy areas, long decision cycles, and sub-optimal funding (Chandrasekhar & Basavarajappa, 2001; Krishnan, 2006).

Third, from an overall perspective, the state continues to accord importance to public R&D in certain high-tech areas, such as space, IT, and pharmaceuticals. Furthermore, public R&D itself has become more commercial and market-driven.

In the case of nanotechnology, according to an estimate, a funding of USD 671.51 million is available to Indian basic and applied research in nanotechnology (**Table 2**). However, this amount is smaller in comparison to the allocations of forerunner countries

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[1] See, Report of the Task Force for Basic Scientific Research in Universities, Set up by Ministry of Human Resource Development Department of Secondary & Higher Education Government of India, New Delhi, May, 2005

in nanotechnology such as USA which has allocated USD 16.9 billion and Japan with USD 9.6 billion during financial years 2002-2013.[2]

Table 2: Nanotechnology funding in India

Type of funding	Year	Amount (USD million)
DST – NanoMission	2007	250.00
DRDO – Nanofoundry	2010	110.00
Rusnano – GoI JV Solar	2010-20	220.00
GoI-DOE (US) Clean Energy Research (5y)	2010	10.00
DST-Max Planck/Science	2010	5.01
DBT-Welcome Trust	-	67.50
DST-RCUK Fuel Cell Research	-	9.00

Source: Compiled by the author based on Bangalore India Nano, 2013[3]

Table 3 shows nanotechnology R&D expenditure by public agencies between the years 2001-2012. Aside from funding R&D, a large part of the nanotechnology budget during the NSTI appears to have been spent on developing the various centres of excellence (CoEs) and establishing laboratory infrastructure. During the NSTM tenure, it appears that copious amounts are being invested in developing human resources in this domain.

Interestingly, prior to the mission funding it had been articulated by government spokespersons that the government alone might be unable to allocate vast sums of investments in nanotechnology due to issues of “resource crunch” and the need to concentrate (and distribute funds across) other priority areas. In fact, the need for public-private partnerships had been espoused as an approach to facilitate pouring of funds into nano-related research and in order to harness it. Nevertheless, a ten- fold increase between the amounts dedicated for nanotechnology research in the NSTI (INR 1000 million) in 2001 and NSTM (INR 10,000 million) in 2007 has been observed.

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[2] Bangalore India Nano. 2013. Sixth Bangalore India Nano Conference held in Bangalore on 4-6 December.

[3] Creating growth opportunities for Indian nanoscience & nanotechnology, Conference Proceeding, Sixth Bangalore India Nano Conference held in Bangalore on 4-6 December.

Table 3: Expenditure on nanotechnology R&D in India by important agencies (2001-2012)[4]

Agency	**R&D Expenditure (INR crores)***
Department of Science and Technology (DST)	567.55 (NSTI – 60; NSTM – 507.55)
Department of Electronics & Information Technology (DeitY)	326.63
Central Manufacturing Technology Institute (CMTI)	67.23
Indian Council of Agricultural Research (ICAR)	10.18
Council of Scientific and Industrial Research (CSIR)	0.78

***** 100 crores ~ 27 million USD

Source: Bhattacharya et al. (2012a)

Other than DST, several other government funding agencies are also supporting the growth of nanotechnology research in India. CSIR is also considered to have invested approximately INR 400 million in this area. Department of Biotechnology (DBT) provides support for nanotechnology in the area of life sciences. CSIR (USD 9 million in 2007–2012) and Science and Engineering Research Council (SERC) also support research projects in diverse areas of nanotechnology, covering both basic and applied sciences. Ministry of Communications & Information Technology (USD 22.49 million in 2010–2011), Indian Council of Medical Research (ICMR), Defence Research Development Organization (DRDO) through its Nanofoundry programme, University Grants Commission (UGC), Indian Space Research Organization (ISRO), Board of Research in Nuclear Studies under the Department of Atomic Energy (DAE), and Indian Council of Agricultural Research (ICAR), have also been funding research programs in the nanotechnology area. A clear picture of the comprehensive investment in nanotechnology is still awaited; however, the efforts of DST in fostering basic research have been the largest in the country. The investments by agencies other than DST might not be in as large in magnitude as funding contributed by DST in the NSTM. Nonetheless, they are also driving significant

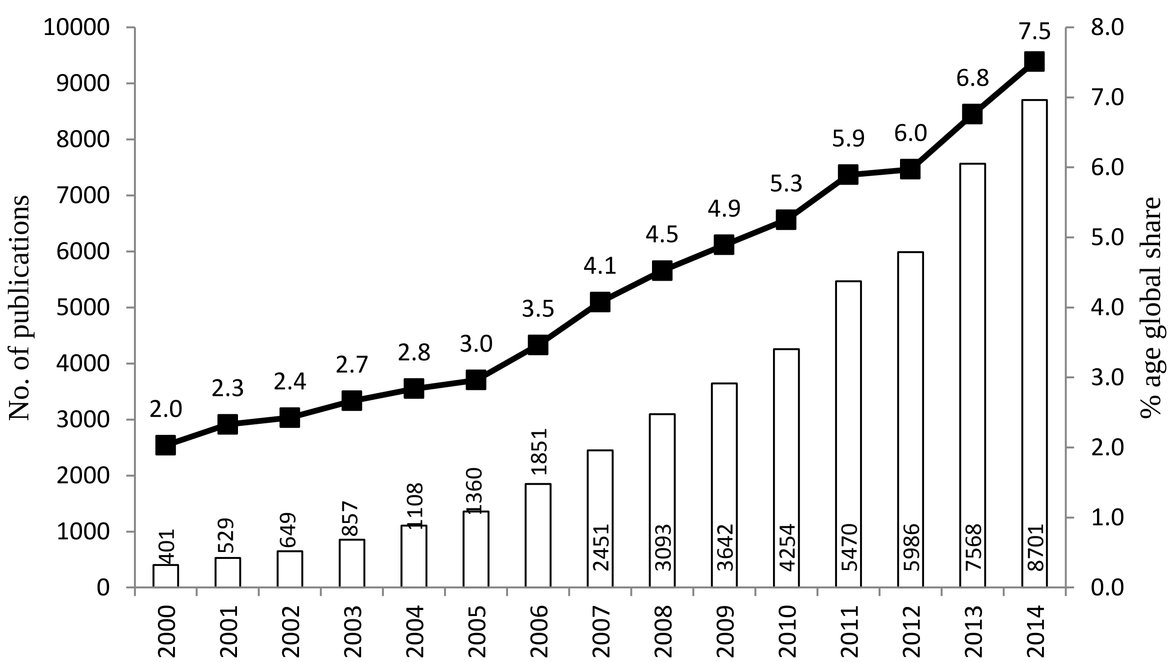
[4] The total reported expenditure is INR 973.37 crores (263 million USD). Besides this, other agencies, including industries, have also made expenditure for which figures are not available (Bhattacharya et al., 2012a)

developments on the ground in terms of developing abilities in nanotechnology in their niche areas.

Additional funding is also available to Indian researchers through joint collaborations such as RUSNANO, RCUK, Max Planck Department of Energy, US Clean Energy Research, etc.

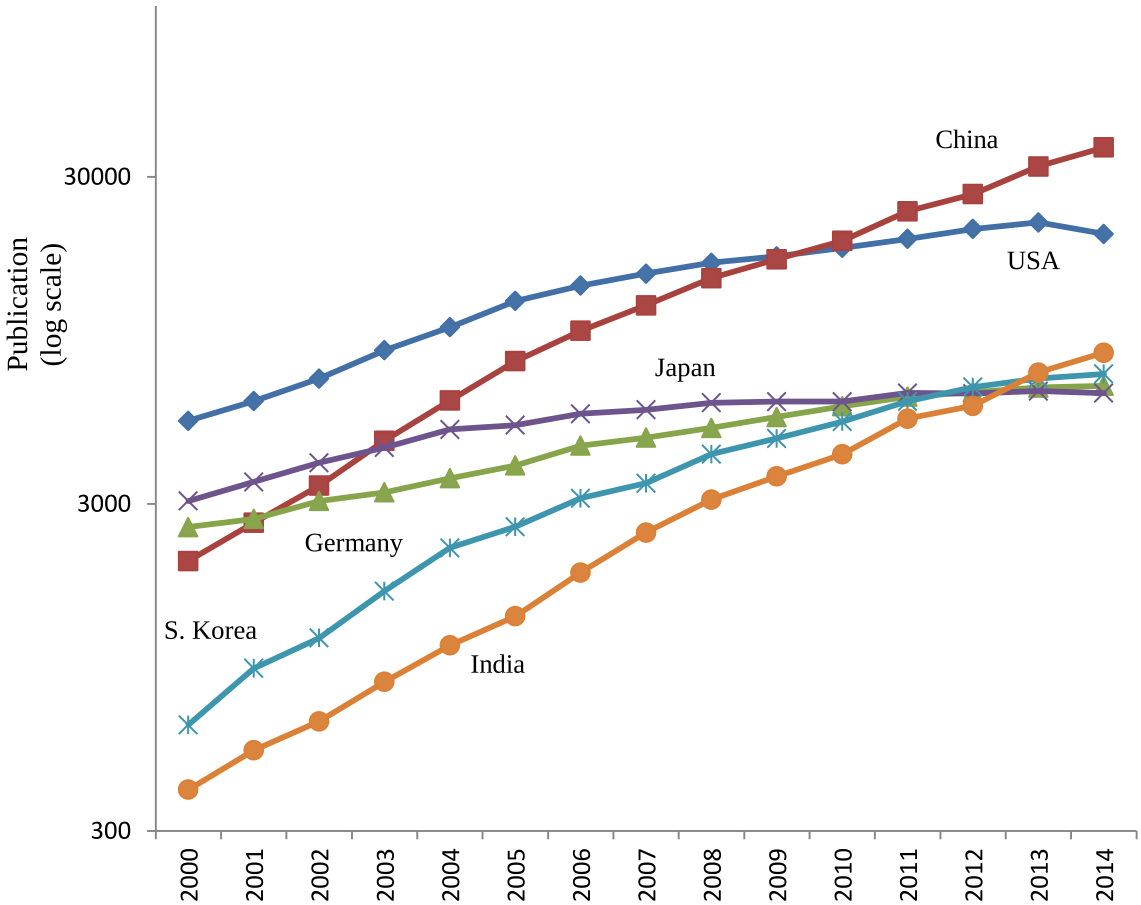
Despite the relatively smaller investment of the Indian state, a substantial expansion in the knowledge base on nanotechnology can be observed over the year. In this regard, India has fared well in nanotechnology in terms of the creation of scientific capabilities as demonstrated by the sizeable generation of scientific publications. Looking at the outcomes, over the years about 5000 research papers have been published by researchers working in the field of nanotechnology and about 900 PhDs have been awarded as a result of the support provided under the Nano Mission (PIB, 2014). In 2014, India accounted for 7.5% of total world production in nanotechnology publications, being 3rd globally (See, **Figure 4** and **Figure 5**). It accounted for 2% of total papers (global rank 13th) in 2000 which went up to 5% in 2009 (global rank 7th).

Figure 4: Publication trends for nanotechnology in India



Source: Author's elaboration based on data from Science Citation Index Expanded (SCI-E)

Figure 5: Publication trends of forerunner publishing countries in nanotechnology



Source: Author's elaboration based on data from Science Citation Index Expanded (SCI-E)

Looking at the activity in different subject fields of nanotechnology in the top 6 publishing countries, reveals that the majority of the publications are in the sub-disciplines of Chemistry, Physics and Materials Science (See, **Table 4**). Publication activity in different sub-disciplines also provides an indication of sectoral research strength and competency.

Table 4: Activity of countries in different sub-disciplines of nanotechnology, 2000-2014

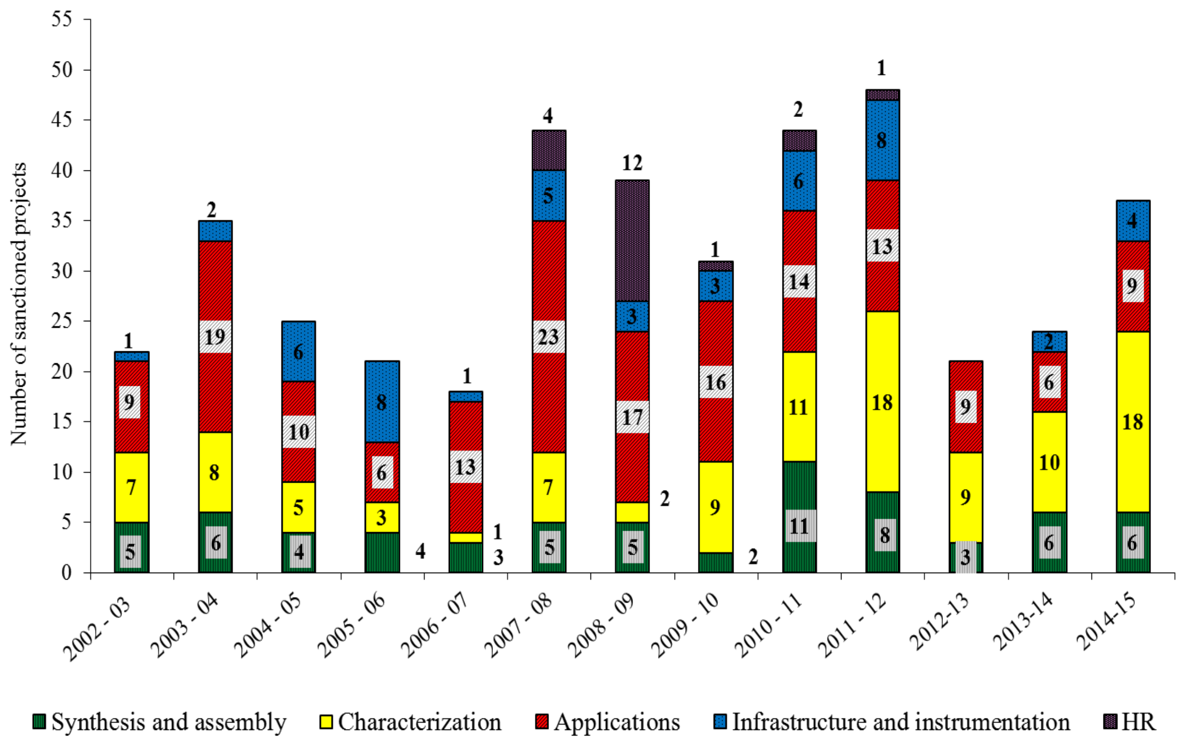
Sub-disciplines	USA	China	Germany	Japan	South Korea	India
Chemistry	85366 (40.0)	96945 (44.2)	23946 (33.4)	26711 (32.8)	21658 (37.5)	17732 (37.0)
Physics	72132 (33.8)	64379 (29.3)	31919 (44.5)	35018 (43.0)	23153 (40.0)	16191 (33.8)
Materials science	67507 (31.6)	84240 (38.4)	22868 (31.9)	26623 (32.7)	25473 (44.1)	19228 (40.1)
Engineering	22941 (10.7)	17631 (8.0)	5536 (7.7)	7439 (9.1)	6335 (11.0)	4273 (8.9)
Polymer science	9571 (4.5)	14096 (6.4)	3829 (5.3)	4476 (5.5)	4254 (7.4)	2694 (5.6)
Biochemistry	8004 (3.8)	3595 (1.6)	2157 (3.0)	1701 (2.1)	974 (1.7)	1154 (2.4)
Toxicology	1164 (0.5)	391 (0.2)	360 (0.5)	268 (0.3)	259 (0.4)	183 (0.4)
Environmental & occupational health	368 (0.2)	41 (0.02)	71 (0.1)	48 (0.1)	33 (0.1)	36 (0.1)
Agriculture	547 (0.3)	503 (0.2)	125 (0.2)	123 (0.2)	84 (0.1)	116 (0.2)
Water	411 (0.2)	451 (0.2)	83 (0.1)	55 (0.1)	127 (0.2)	101 (0.2)

Note: Figures in parenthesis indicate percentage share of total publications in nanotechnology of the respective countries

Source: Author's elaboration based on SCI-expanded database

The bulk of the projects supported by the NSTI and NSTM are in the area of synthesis, characterization, processing which help to develop an understanding of the unique properties of nanostructured materials (See, **Figure 6**).

Figure 6: Distribution of nanotechnology projects supported by DST across basic and applied research/product development and other areas

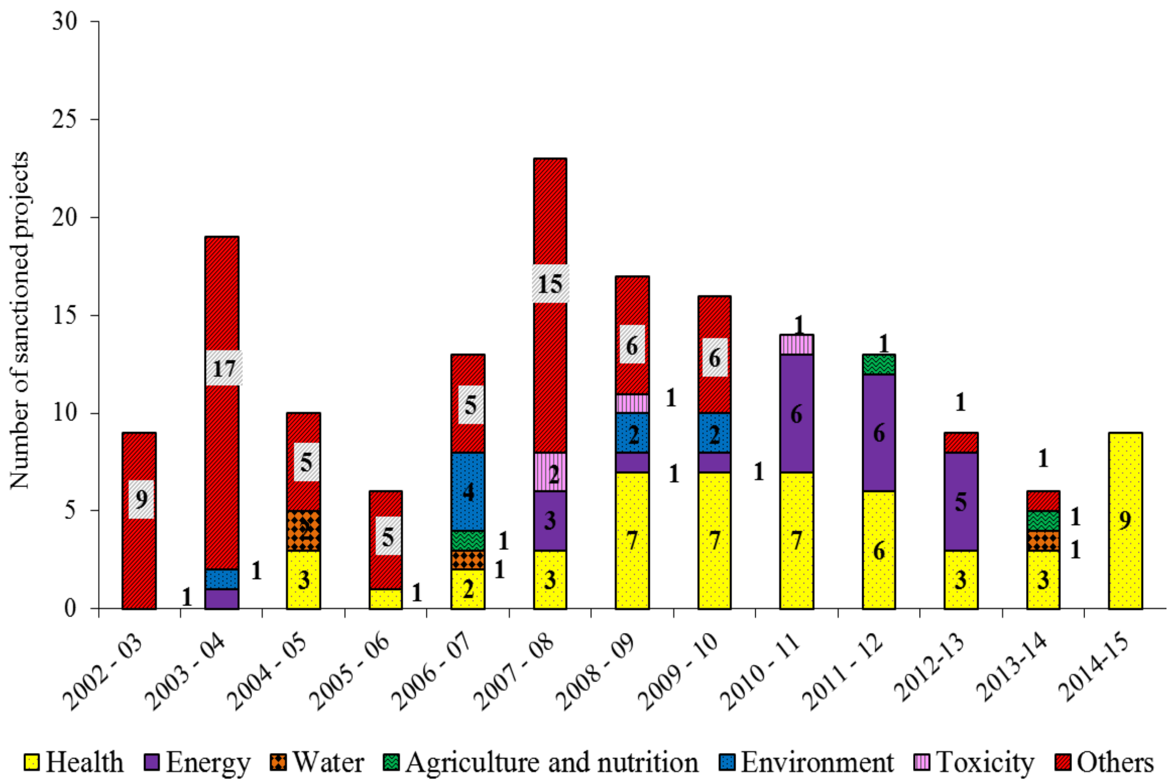


Source: Author's elaboration based on information on nanotechnology related projects supported for various years available from the Nano Mission and DST website (http://nanomission.gov.in, http://dst.gov.in/scientific-programme/ser-serc.htm)

Research on a variety of nanomaterials such as metallic, metal oxide, semiconductor, magnetic nanoparticles, quantum dots carbon nanotubes and other nanocomposites, polymeric nanomaterials, nanofilms, nanowires, nano alloys, nanoporous solids have been undertaken and a wide range of routes for synthesis of nanomaterials including sol-gel, salvo-thermal, spray pyrolysis, chemical vapour synthesis etc. have been explored. Also, an emphasis has been put on exploring the industrial applications of these materials besides focusing on the development of nanolithography and nanofabrication techniques. Furthermore, a significant number of projects have been supported in basic and applied research in the area of physical and chemical sciences. For example, in physical sciences, nanotechnology research in India covers areas of condensed matter physics and materials science; plasma, high energy, nuclear physics, astrophysics and nonlinear dynamics as well as laser, optics, atomic and molecular physics.

Initially the projects supported by the NSTI and NSTM had no particular sectoral orientation, but increasingly they are focussed on the health sector and environment (See, **Figure 7**). For example, in the area of health, there has been considerable research focus on targeted drug and gene delivery (therapeutics), diagnostic systems and biosensors as well as the use of biomaterials for various applications including regenerative medicine. Significant technological achievements have been achieved in this application area, e.g., encapsulation of water-soluble drugs using hydrogen nanoparticles developed through reverse micelles based process.

Figure 7: Sector-wise distribution of application oriented R&D projects in nanotechnology supported by DST



Source: Author's elaboration based on information on nanotechnology related projects supported for various years available from the Nano Mission and DST website (http://nanomission.gov.in, http://dst.gov.in/scientific-programme/ser-serc.htm)

With respect to environment, the thrust is on the application of nanomaterials, particularly nano-scale silver and carbon nanotubes in water purification. Various technologies have been developed in this area such as incorporation of nano silver in traditional candle filters for disinfection, nano silver based carbon blocks for pesticide removal, nano silver coated alumina catalyst for controlling microorganisms in water, carbon nanotube filters for bacteria removal, and nano iron oxide/mixed oxide for arsenic removal.

In the energy sector, the basic aim is to improve the solar photovoltaic process efficiency, making solar cells more cost-effective, and search for alternate semiconductors in lieu of silicon shortage through development of new materials, processes, device structures.

4. Innovation capabilities

The accumulation of scientific capabilities does not guarantee the automatic build-up of technological and innovation capabilities. This is proved by the few start-ups and the handful of large firms which have incorporated nanotechnology-based processes in their production systems, despite the hype about nanotechnology. According to an estimate, of about 500 nanotechnology companies, 200 with commercial products already exists in the Indian market in 2013.[5] An analysis of companies[6] actively operating in India in the field of nanotechnology revealed that the largest numbers of organisations involved in nanotechnology are *intermediary product developers* (176 companies) which are essentially application developers followed by *nanomaterial companies* (117 companies) in which majority of them offer trading services whereby the nanomaterials is imported from a parent or collaborating company overseas. There are then *end product companies* (112 companies) that are large scale industrial groups that have developed an interest in incorporating nanotechnology in an incremental manner for their existing product lines. *Instrumentation companies* are the smallest group (25 companies), where the primary activity is importing the scientific instrumentation from abroad besides a handful of

[5] Bangalore India Nano. 2013. Sixth Bangalore India Nano Conference held in Bangalore on 4-6 December.

[6] Ibid.

instrumentation companies having local or indigenous manufacturing capabilities. The largest sector of market impact from nanotechnology activities is chemical and materials followed by medicine, construction, environment, energy, automotive, textile, aerospace, security and defence.

Looking at the markets accessed by companies in India with an interest in nanotechnology, it is observed that companies have a varied scale of supply chain development across the country and the world. The biggest chunk of companies includes wholly owned subsidiaries of international conglomerates having India focus (245 companies) for whom India remains the primary market of access and focus. A limited number of Indian origin companies have developed supply chains in the Asia-Pacific (39 companies) or the Global region (37 companies) and the least accessed markets for these companies remain Europe (19 companies) and North-America (15 companies).

A majority of the companies in India with an interest in nanotechnology have *manufacturing* (243 companies) as the primary area of focus with activities ranging from end products across industrial supply chains to nanomaterials production. There are companies that offer solely services (68 companies) in nanotechnology in India such as, trading of nanomaterials, consultancy services in intellectual property, strategy or technology transfer, etc., while some companies offered both manufacturing and trading services. Research and development as a contractual service (21 companies) is only offered by a very small fraction of firms largely focused on life sciences and nanomedicine developments.

When assessed in terms of the geographic location of companies, the highest number of companies are located in Western India (134 companies) including states of Maharashtra, Gujarat and Rajasthan followed by companies in South India (79 companies) comprising of states of Andhra Pradesh, Karnataka, Kerala and Tamil Nadu. This is followed by companies located in North Indian states and the National Capital Region (71 companies) and companies located in Eastern India (15 companies).

Comparative assessment of the size of companies involved in nanotechnology in India reveals that small enterprises (98 companies) with employee strength of 10-100 and medium-sized enterprises (89 companies) with employee strength of 100-1000 are the most active entities developing nanotechnology. Large scale enterprises (72 companies) are active integrators of products containing nanotechnology. Micro scale enterprises (39 companies) with a size of less than 10 employees are providing development or trading services focused on nanotechnology.

In terms of consumer products, a number of nanotechnology based innovations are supposed to be available to various segments of Indian consumers. However, it is extremely difficult to keep track of them as they are dispersed in a variety of sectors forming a component or a part of the production process of established products.

Thus, although at its nascent stage, the nanotechnology market globally is anticipated to grow at a Compounded Annual Growth Rate (CAGR) of around 17.5 per cent during 2016-2022 (RNCOS, 2015). According to estimates by market research and industry analysis, the global opportunity for nano-based products was 11.67 billion US$ in 2009 (BCC, 2010). The current market size of nanotechnology in India is around INR 10,000-15,000 crores and about 1500 nano-based products are in the market. As per the estimates of Centre for Knowledge Management of Nanoscience & Technology (CKMNT), over the next 10-15 years the domestic nanotechnology market will grow up to $1.6 billion at a CAGR of 47 per cent, with the potential to reach 2.1 billion US$.[7] However, the in-house nanoproducts which have been developed by leading local Indian companies are basically the low hanging fruits such as nanocomponents in diagnostics, nano-sensors, and nano-devices. This is an excellent start – but the technological challenges are going to increase as the low hanging fruit get picked and there is a need to reach higher. Again, there will be a need for upscaling the production of the low hanging fruit and reducing costs to better serve various income groups and achieve competitiveness.

The knowledge base of any organization or region in terms of patents depends on the 'search strategy' as well as the 'database used'. Often the results are very different as a function of the above. Bhattacharya et al. (2012b), examine the patents issuing from India in the USPTO (US patent office) under the class '977' signifying affiliation to

[7] http://www.pressreader.com/india/biospectrum-india/20141201/281595238877442/TextView

nanotechnology, and identify 12 filings between 2000 and 2009 out of which 7 have been granted. Ramani et al. (2010), also confirm 35 patent applications in the EPO, (European Patent office) under the class ‘Y01N’ which is the tag applied to nanotechnology. On the other hand, Gupta (2009) uses a string of indicative keywords to identify a total of 167 patent applications related to nanotechnology issuing from India between 2001 to 2007 deposited in patent offices in the USA, Japan, Germany, Europe (EPO), and WIPO (World Intellectual Property Organization), INPADOC (International patent documentation centre). All these studies show that in the international arena universities and public laboratories are the most active patentees. Hence, technology transfer from universities and public laboratories to companies may be a key issue in the commercialisation of nanotechnology.

Using the keyword “nano” yields a total of 166 granted patents by the Indian Patent Office (IPO) during the period 1997-2009. Of these, a total of 91 patents had been assigned to Indian entities. Of the total 166 patents, 75 patents (45% of the total patents) are owned by firms in the industry, 40 patents (24% of the total) by academic institutions, and 35 patents (21% of the total) by government institutions. There are 15 patents (9% of the total) that are owned by individual inventors, and 1 patent is being jointly held by government institutions and firms from industry. **Table 5** shows the distribution of patent applications in nanotechnology at the IPO across institutional sectors and nationalities.

The scientific research organization owning the majority of patents include laboratories of the Council of Scientific and Industrial Research (CSIR). Among the academic institutes, the IITs have been the major contributors of nanopatents at the Indian Patent Office (IPO). In the industry sector, foreign companies are the major patent holders. Among Indian firms, nanopatents are being held by firms like Ranbaxy Laboratories Limited (Indian company till 2007), Dabur India Limited, Nano Cutting Edge Technology Private Limited, and Lifecare Innovations Private Limited.

The major technology areas of patenting in nanotechnology include applications related to drugs and pharmaceuticals, chemical science and technologies e.g. colloid chemistry, catalysis, separation of non-metallic elements and materials, analyzing materials by determining their physio-chemical properties, and filters implantable into blood vessels.

Table 5: Analysis of patent applications at IPO between 1997 to 2009 – Type of patent assignees and sectors

Category	Indian	Foreign	Total
Type of patent assignees			
Individual inventors	13	2	15
Academic institutes	33	7	40
Government organizations	34	1	35
Industry	10	65	75
Joint patents	1	-	1
Sectors			
Nanomaterials	-	-	17
Process for making nanomaterials	-	-	139
Devices	-	-	10

Source: Author's elaboration based on data from Indian Patent Office

Patent data may also be useful to understand areas in which economies are relatively specialized and those in which they lag behind. The revealed technology advantage (RTA) index provides an indication of the relative specialization of a given country in selected technological domains and is based on patent applications filed under the Patent Cooperation Treaty (PCT).[8]

Table 6 compares the patent filings of select countries in information technology, biotechnology, and nanotechnology. Overall, nanotechnology patenting grew by around 43% during 2003-2013, with a very high growth observed in the countries of China and South Korea, the latter becoming the most specialized nanotechnology economy. Patenting in biotechnology decreased by almost 10% over the same period, with China and South Korea followed by India witnessing a high growth rate. Countries like USA

[8] Revealed technology advantage (RTA) index is defined as a ratio of country's share of patents in a particular technology field to the country's share in all patent fields. RTA index is equal to zero when the country has no patents in a given field, it is equal to 1 when the country's share in a given sector equals that country's share in all fields (no specialization), and the index is above 1 when a positive specialization is observed.

and India demonstrate a high technological superiority in biotechnology. Overall, patenting in information technology grew by 40%. Although there was not much increase in patenting in the Triad countries (USA, EU, Japan), China, Korea, and India witnessed a significant increase in patenting in information technology, with the former two countries along with Japan exhibiting specialization in this field.

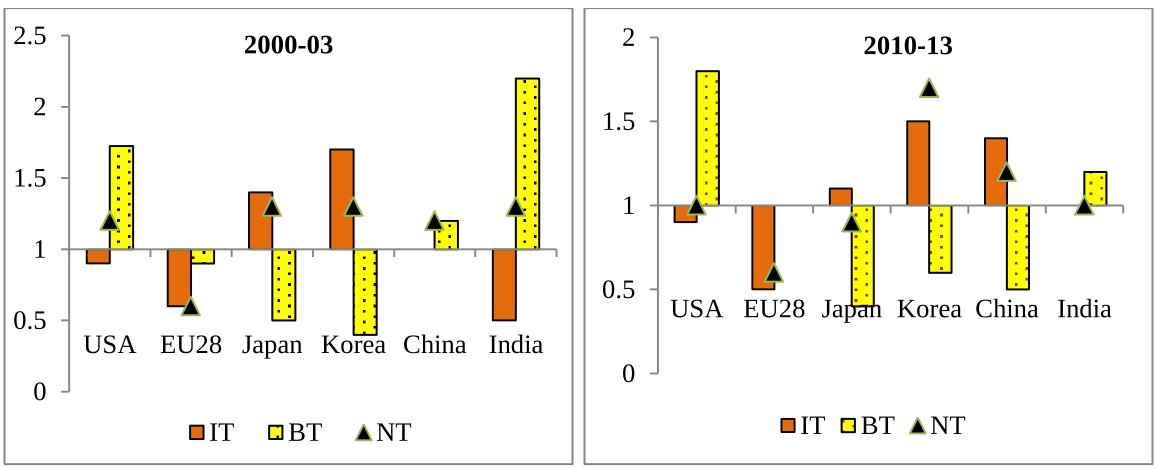
Table 6: Number of patent families in information technology, biotechnology and nanotechnology under the PCT, 2000-03 and 2010-13

Country / Region	**Information technology**			**Biotechnology**			**Nanotechnology**		
	2000-03	**2010-13**	**Decadal growth (%)**	**2000-03**	**2010-13**	**Decadal growth (%)**	**2000-03**	**2010-13**	**Decadal growth (%)**
USA	60,481	65,806	8.8	16,532	13,245	-19.9	2,390	2,510	5.0
EU 28	51,964	52,530	1.1	10,724	10,374	-3.3	1,503	1,847	22.9
Japan	94,230	112,679	19.6	5,030	4,106	-18.4	2,813	2,883	2.5
Korea	20,347	54,435	167.5	673	2,139	217.8	458	1,933	322.1
China	1,590	28,517	1693.5	282	1,076	281.6	58	779	1243.1
India	334	2,402	619.2	216	303	40.3	26	74	184.6
World	259,866	363,636	39.9	39,652	35,771	-9.8	7,931	11,306	42.6

Source: Author's elaboration based on data available from the OECD website (https://stats.oecd.org)

The revealed technological advantage index applied to data from the International Patent Classification (IPC), as shown in **Figure 8**, provides an indication of the relative specialization of these economies in information technology, biotechnology, and nanotechnology. The RTA values reveal that most economies do not seem specialised in specific technology fields with the median RTA being equal to or less than 1. However, some pattern of technological specialization could be observed across economies and fields. For instance, RTA values for 2010-13 suggest that Korea and China display specialisation in nanotechnology and information technology, with Japan also showing specialization in the latter field. However, they are yet to prove superiority in biotechnology. On the other hand, the countries of US and India demonstrate specialization in biotechnology, with the potential of gaining technological expertise in nanotechnology. The primary focus in these three technology platforms is devising a solution to global issues relevant to sustainable growth and materializing productivity boosts in different sectors.

Figure 8: Revealed technology advantage in information technology, biotechnology, and nanotechnology, 2000-03 and 2010-13



Note: Index based on patent applications filed under the Patent Cooperation Treaty (PCT)

Source: Author's elaboration based on data available from the OECD website (https://stats.oecd.org)

5. Technology diffusion

To understand the key factors affecting diffusion of emergent technologies scholars have emphasized on the processes of network influence and information flow (see, Burt, 1992; Attewell, 1992; Allen, 1977) as the central explanation for the spread of technology related innovations. It is expected that increased information flow in today's world, largely facilitated through the internet, is enabling entry of a large number of players in various technological trajectories, particularly in terms of their scientific contributions.

But are these developments also enabling technology development and diffusion is a key question that needs to be addressed in an emerging technology and whether the technology development and diffusion rate is typical of an emerging technology?

To understand this, a comparison of technology diffusion rates of first 100 nanopatents to the diffusion of recombinant DNA in the area of biotechnology would be useful. Recombinant DNA is considered to have been one of the most important emergent technologies in the recent past and is also an important pro-genitor technology in the generic field of nanotechnology. In a study conducted by Reid and Pliniussen (2002), recombinant DNA reached the 100-patent benchmark within 8 years, starting with a first patent applied for in 1978 and issued on 1980. In comparison, the first nanotechnology-related patent (measured by the rate of growth of patenting activity in the area of nanostructures) issued in 1981, has taken 20 years to reach the benchmark of 100-patent. Thus, it could be observed that nanotechnology is diffusing far more slowly than biotechnology.

Based on this same data, it was also observed by Niosi and Reid (2007) that fewer than 20% of the patents granted in the field of recombinant DNA were granted outside of the USA (USPTO database) to foreign patent applications, whereas in the case of nanotechnology approximately 45% of the granted patents related to nanostructures have been granted outside of the USA. A key question at this point is, whether such dispersions slow down the diffusion process of an emerging technology within a country?

The Indian patenting activity in the domain of biotechnology and nanotechnology, investigated for the period 1995 post-TRIPS to 2011, are shown in **Table 7** to **Table 9**. As observed from the Tables, in the Indian case too, in comparison to biotechnology, the progress in the field of nanotechnology has occurred at a much slower rate.

The slow diffusion in nanotechnology could be explained by the fact that since nanotechnology is built upon many sciences viz., molecular biology, electronics, materials science, physics, chemistry, and others, such a combination of multiple complex technologies would take a longer time to evolve leading to slow rate of technology diffusion in this area (Iansiti & West, 1997). Further, a limited number of researchers having expertise in working in an interdisciplinary fashion provides a challenge in technology diffusion and adoption in this emergent field.

Table 7: Indian nanotechnology and biotechnology patents at USPTO

Year	Nanotechnology		Biotechnology	
	World	**India**	**World**	**India**
1995	45	0.0	1,138	1.0
1996	227	0.0	2,630	0.7
1997	757	0.0	4,949	1.2
1998	559	0.0	6,293	9.6
1999	757	0.8	7,921	11.1
2000	2,340	2.6	16,504	25.9
2001	3,464	6.6	20,641	95.3
2002	4,063	12.5	21,244	110.5
2003	4,021	15.7	19,285	96.0
2004	4,566	14.6	17,473	110.7
2005	4,844	12.4	16,535	114.6
2006	4,203	12.3	16,086	123.3
2007	4,108	14.6	16,266	87.7
2008	4,369	18.1	14,864	102.7
2009	4,323	30.5	13,551	94.1
2010	4,229	43.9	12,165	95.2
2011	4,167	36.8	10,653	84.2

Note: Country patent figures are based on fractional counts, which imply that each country affiliation of inventors is given a proportional allocation of patents.

Source: Author's elaboration based on data available from the OECD website (https://stats.oecd.org)

The factors impacting rates of diffusion could also be explained by Rogers' framework (1983) of diffusion and adoption of innovation. According to Rogers (1983), the attributes of innovations which help to decrease uncertainty about the innovation and impact the speed of diffusion includes: relative advantage, compatibility, complexity, trialability, and observability. These predictors for the rate of adoption and diffusion of innovations in the life of an emerging technology will determine the level of complexity in terms of the integration of pro-genitor technologies which would influence technology development and collaboration avenues.

Table 8: Indian nanotechnology and biotechnology patents at EPO

Year	Nanotechnology		Biotechnology	
	World	**India**	**World**	**India**
1995	396	0.4	4,781	4.5
1996	505	0.0	5,431	7.5
1997	570	0.2	6,507	6.2
1998	654	0.0	7,611	16.1
1999	848	0.3	9,058	23.9
2000	1,056	2.1	9,624	32.1
2001	1,235	2.5	9,604	30.1
2002	1,461	3.0	9,348	47.9
2003	1,427	12.3	8,970	52.5
2004	1,583	4.4	8,500	50.3
2005	1,559	5.3	8,534	57.7
2006	1,357	6.6	8,127	72.9
2007	1,305	8.3	8,204	38.4
2008	1,190	11.6	7,431	61.0
2009	1,204	6.2	6,910	53.6
2010	1,187	11.3	6,852	55.1
2011	1,114	6.8	6,818	55.0

Note: Country patent figures are based on fractional counts, which imply that each country affiliation of inventors is given a proportional allocation of patents.

Source: Author's elaboration based on data available from the OECD website (https://stats.oecd.org)

In the case of biotechnology, as noted by Kogut (1991), in the US biotechnology industry research networks are quite central and are clustered around a few key public and private organizations. This has enabled development of a common language for interaction and has facilitated closer interaction among researchers allowing them to spend time together at conferences, meetings and during collaborative work. Such a close interaction and cooperation among researchers had strengthened trialability and observability attributes by enabling trying out and observation of techniques and theories with other researchers. Further, the relative advantage and reduced complexity attributes of innovation in recombinant DNA technology, in terms of pro-genitor technologies allowed even further increase in diffusion rates. The different pro-genitor technologies of the recombinant DNA technology mostly originated from the field of molecular biology. As such, capabilities already existed amongst the research population which needed to be built upon to engage with biotechnology.

Table 9: Indian nanotechnology and biotechnology patents at PCT

Year	Nanotechnology		Biotechnology	
	World	**India**	**World**	**India**
1995	284	0.2	4,739	3.2
1996	328	0.0	5,554	2.3
1997	423	0.2	6,560	1.3
1998	520	0.0	7,941	8.2
1999	724	0.3	10,010	24.8
2000	1,008	2.4	12,263	38.3
2001	1,347	2.5	11,814	48.1
2002	1,523	6.5	11,255	73.3
2003	1,681	19.4	10,791	76.0
2004	1,983	7.9	10,277	72.5
2005	2,070	9.8	10,162	81.7
2006	2,025	12.3	10,219	92.7
2007	2,052	10.1	10,797	75.5
2008	1,915	18.1	10,150	108.1
2009	1,959	16.7	9,778	104.4
2010	2,081	28.6	10,391	120.1
2011	2,193	24.4	10,619	109.7

Note: Country patent figures are based on fractional counts, which imply that each country affiliation of inventors is given a proportional allocation of patents.

Source: Author’s elaboration based on data available from the OECD website (https://stats.oecd.org)

However, in the case of nanotechnology, while increase in information flow, largely facilitated through information and communication technology, and the existence of global manufacturing facilities, have enabled foreign players to enter technology development trajectories earlier than once was the case. However, the geographical dispersion of technological capability, as indicated by the patent ownership trends, may be an impediment to diffusion. The wide dispersion also hinders the development of a common language and impedes localized exchange, both in terms of the physical and industry distance in networks (Sorenson & Stuart, 2001), thereby impacting the potential for trialability and observability. Further, the pro-genitor technologies which contribute to the field of nanotechnology have diversified disciplinary orientation varying both in kind and degree. As such, a more diffused network and the complexity of combining multiple generic technologies may have a greater combined differential effect on diffusion rate than increase information flow in networks. These initial technological capabilities dispersion tends to persist over time and will have an impact on the future product capabilities of firms and their geographical dispersion. (Kogut, 1990; Sorenson & Stuart, 2001).

6. Policy thrust

A chronological overview of key policies and programmes related to nanotechnology development in India is given in **Table 10**. Recurring themes are building research capabilities in high technology areas and its applications, creation of quality manpower through the establishment of research infrastructure in nanotechnology, promotion of international collaborative programmes, and strengthening of industry-research institute/academia linkages through public-private partnerships.

Table 10: Historical overview of key policies & programmes on nanotechnology in India

1980-85	Intensification of Research in High Priority Areas (IRHPA)
• To strengthen research in frontline and emerging fields of science and engineering through setting up of Core Groups, Centres of Excellence and National Facilities	
1997	Programme on Nanocrystalline Materials
• Funded projects focused on synthesis and properties of nanomaterials was initiated	

	by SERC placed under DST
2000	The National Programme on Smart Materials
	• The 5 year programme launched jointly by five government agencies - DRDO, DoS, CSIR, DST and DeitY focused on aerospace and biomedical sciences • Around 15 million USD granted to support development of applications, processes and technologies in the sphere of nanotechnology amongst other areas. Special emphasis was laid on issues of national importance such as access to clean water, alternative energy sources etc. • Considered instrumental for future independent initiatives in micro and nanotechnology
2000	Expert group on Nanomaterials
	• To comment on the existing expertise in the nanotechnology domain in India and the direction for the future. • Highlighted need to encourage greater basic as well as goal oriented applied research within the country together with enhancinginfrastructural capacities. • Research in the areas of chemical synthesis of nanomaterials, nano ceramics alongside development of nanomaterials for nano drug delivery and water purification were identified as key areas
2001	Nano Science and Technology Initiative (NSTI)
	• Funded at INR 100 crore (approximately 15–20 million USD) by DST • Aimed at supporting R&D projects in nanotechnology; establishment of Centers of Excellence and strengthen characterization facilities; develop human resources; instigate and encourage international collaborative programs; and, initiate joint institute-industry linked projects and Public-Private Partnership activities
2004-05	Nanotechnology Development Programme
	• Started by Department of Information Technology under its Nanotechnology Initiative Division created to develop R&D in the area of nanoelectronics and nanometrology • Focus has been on developing infrastructure within institutes in these areas and supporting projects in these areas

• Around INR 25–40 crores each year between the years 2004–2007 have been spent on this programme	
2007	Nano Science and Technology Mission (NSTM)
• Launched by the DST with a budget of INR 1000 crore (approximately 254 million USD) for a 5-year duration (2007–2012) • To leverage the progress made during the NSTI to further intensify and consolidate basic research in nanotechnology, promote and support goal oriented R&D for developing applications, create greater number of infrastructural facilities, strengthen human resources, and enhance collaborations	
2008 • Introduction of PG programmes in nanotechnology by Nano Mission; INUP initiated by IISc & IITB (Funded by DeitY, MCIT)	
2010 • Nanotechnology Intervention in Mission Mode Programs (Solar, Water)	
2012 • Nano Mission to provide loans and grants to the Industry to develop nano applications	
2014 • Union Cabinet approval for continuation of Nano Mission earmarking INR 650 crore for the second phase (2012-2017)	

Source: Compiled by the author

The above-mentioned policies and programmes on nanotechnology, led to public investment in the scientific community and infrastructure in universities and public laboratories. Particularly, the NSTI and NSTM have facilitated the creation of an ecosystem to pursue basic research in nanotechnology as well as application-oriented R&D, focused on useful technologies and products. The government of India under the NSTI and NSTM of DST had so far influenced nanotechnology development in India in the following manner:

6.1 Nano S&T infrastructure development

Strengthening of characterization facilities and establishment of centres of excellence (CoE) are the main infrastructure development programmes supported under the Nano Mission. Nanotechnology research requires sophisticated characterization facilities which were mostly not available in Indian S&T institutes. NSTI and NSTM have identified the need to establish facilities for the characterisation of nanomaterials and to serve other analytical needs. To enable researchers access to sophisticated equipment, centres for sophisticated analytical instrument facilities (SAIFs) have been set up across India. These centres are located at major research hubs and at institutions capable of hosting such facilities, where researchers from all parts of India can avail scientific equipment on a payment basis. The establishment of a chain of such facilities that house instruments like AFM, TEM, STM as well as optical tweezer, nano indent, etc. which could be used on a shared basis has been considered for promoting nanotechnology research. It appears that all the CoEs also harbour the equipment needed to engage with nano research. Specific institutes have been provided financial support to upgrade their analytical facilities and tailor them to the specific needs of nanotechnology (**Table 11**). Apart from these, support for facilities at established CoEs like IISc and JNCASR, institutes like Bangalore University, University of Madras, as well as the Inter University Accelerator Center at New Delhi, have also been provided with grants for this purpose. Additionally, research on developing novel tools for construction of nanomaterials has also been supported at IIT Mumbai.

The DeitY has initiated development of joint nano-electronics centres at IISc Bangalore and IIT Mumbai to combine strengths of these two institutes. It was felt that this approach would drive interdisciplinary research in the context of developing nanomaterials for electronic applications as well as technology development by the way of nanodevices, etc. Another key step taken by DeitY towards strengthening research capacity is the Indian Nanoelectronics User Program (INUP) is to enable researchers outside these two premier institutes to avail the infrastructure available for nanoelectronics R&D at these centres. The programme aims at creating a common platform for an exchange of ideas and expertise for advances in this field.[9]

Table 11: List of initiatives taken during the NSTI and NSTM to upgrade infrastructure facilities

Year	Financial support for analytical facilities
2003-2004	− Design of new and novel nanoconstruction tools – *IIT, Mumbai* − Construction of an optical tweezer for nanometer scale rheology – *Bangalore University, Karnataka* − Up-gradation of existing UHV chamber preparation and investigation of the properties of nanostructured materials – *University of Madras, Tamil Nadu* − Development of state-of-the-art analytical electron microscopy facility capable of high-resolution imaging and analysis in the nanoscale as an institute facility – *Indian Institute of Science, Karnataka*
2007-2008	− Clean room infrastructure for national nanofabrication centre – *Indian Institute of Science, Karnataka* − National facility on ultra high resolution aberration-corrected transmission electron microscope – *International Centre forMaterials Research, JNCASR, Karnataka*
2008-2009	− Augmentation of computing resources for simulation and data analysis – *Inter University Accelerator Centre, New Delhi*
2009-2010	− Institute of Nano Science and Technology at Mohali (INST-Mohali) registered as an autonomous society for research in the areas of agri- and bio nanotechnologies
2010-2011	− 6 new Units/Research facilities on Nano Science established

[9] http://www.inup-iitb.org/workshop.html

2011-2012	− Eight new Thematic Units of Excellence established on focused themes viz., Tissue Engineering and Medical Bio-Nanotechnology; Nanomaterial-based Technologies for Automotive Applications; Physics and Technology of Nano Assemblies; Soft Nanofabrication with Applications in Energy, Environment and Bioplatforms; Nanochemistry; Nano Device Technology; Water Purification using Nanotechnology; and Computational Materials Science
2012-2013	− 2 new Thematic Units of Excellence on Computational Materials Science and 1 major project on Computational Materials Science supported

Source: Compiled by the author based on information available from the Nano Mission website (http://nanomission.gov.in)

6.2 Human resources development

Human resource development is one of the main objectives of the NSTM, towards which the mission seeks to provide exposure to both students and researchers in the diverse fields that partake in nanotechnology and prepare them to work across disciplines, which is the hallmark of science-based technological field like nanotechnology. The Nano Mission apart from leveraging the potential of a large population and young workforce seeks to harness the and low-cost R&D advantage to entice global firms and investment and make India the "global destination for nano research".[10]

DST has issued notices inviting universities and research institutes to initiate postgraduate courses (M.Sc. or M.Tech.) in nanotechnology. It proposed 5-year financial assistance to institutes that possess adequate infrastructure and can train students in multidisciplinary disciplines that is necessitated for teaching in nanotechnology. Since 2007, funds have been granted to several academic institutes to undertake postgraduate courses and provide education in the area of nanotechnology. The aim is to build a pool of skilled personnel across the spectrum of post graduates, doctoral students as well as scientists that is essential to sustain the growth of nanotechnology in India.

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[10] National mission to make India global nano hub, 11th May 2007. Available at, http://www.indiaprwire.com/businessnews/20071105/25368.htm

These courses have been proliferating at various institutes across different regions of India. DST has facilitated postgraduate courses in nanotechnology at around 17 institutes/universities in India until now. A look at some of the postgraduate courses facilitated by DST (**Table 12**) reveals that there is greater interest in M.Tech. courses in comparison to M.Sc. courses. In general, M.Sc. courses train students for undertaking research as a profession in either basic or applied disciplines. M.Tech. courses, on the other hand, are configured towards engineering disciplines and help develop a workforce empowered to undertake technology development in the chosen field. The predominance of M.Tech. courses over M.Sc. courses suggests that policy makers might be trying to orient human resources development in the nanotechnology sphere predominantly towards engineering and application development avenues.

This might enable development of a workforce capable of engaging with nanotechnology in the industry domain. At present, industry participation in this field is in its infancy in India. Moreover, start-ups and SMEs are in a minority amongst those industrial organisations engaging with nanotechnology in India. Therefore, the evolution of M.Tech courses might help fill this gap and instigate the development of products and devices, an area that NSTM has emphasized, at a more rapid pace than previously.

Table 12: List of post-graduates course in nanotechnology facilitated by DST

Year	PG Teaching Programmes	University/Institute
2007-2008	2 Year M.Tech.	Anna University, Chennai - Annual intake of 15 Students
	2 Year M.Tech.	Indraprastha University, New Delhi - Annual intake of 15 Students
	2 Year M.Tech.	Jadavpur University, Kolkata - Annual intake of 18 Students
2008-2009	2 Year M.Sc.	Guru Nanak Dev University, Amritsar - Annual intake of 15 students
	2 Year M.Tech.	SASTRA University, Thanjavur - Annual intake of 20 students
	2 Year M.Tech.	Guru Jambheshwar University of

		Science & Technology, Hisar - Annual intake of 20 students
	3 Year Integrated M.Tech.	University of Delhi
	3 Year Integrated M.Tech.	Vellore Institute of Technology University, Vellore
	M.Tech.	Aligarh Muslim University, Aligarh
	2 Year M.Sc. in Nano Physics	Osmania University, Hyderabad
	M.Tech. in Nano Medical Science	Amrita Institute of Medical Sciences, Kochi
2009-2010	M. Tech. in Nano Science and Technology	Jawaharlal Nehru Technological University (JNTU), Hyderabad - Annual intake of 20 students
2010-2011	M. Tech. in Nano Science and Technology	At 2 institutes in India

Source: Compiled by the author based on information available from the Nano Mission website (http://nanomission.gov.in)

In other spheres, training programs including those at set ups like the INUP have built the capacity of researchers in the nanotechnology domain. In fact some of DSTs general training schemes for scientists such as 'The Foundation Training Program' as well as the 'Advanced Techno-Management Program for Scientists and Technologists (Middle Level)' also cover nanotechnology. Several other initiatives undertaken under the NSTI and NSTM for strengthening human resource development are listed in **Table 13**.

Other departments have also extended support for developing human resources in their niche areas. For example, DBT has awarded overseas fellowships to scientists for training in nanotechnology; conferences and workshops on nanotechnology through ICMR and CSIR support; ICMR Fellowship has been awarded for training in nanotechnology and drug delivery. MNRE is planning to establish research centres that might focus on key nanotechnology and its application in the energy sector.

Given that nanotechnology is an enabling technology and draws from several disciplines, the research community is spread out across areas of expertise, disciplines, institutes and centres. Nano Mission is maintaining a database or directory that lists the expertise in nanotechnology in India. This would enhance information flows amongst the R&D community and help build networks for cross-disciplinary collaborations.

The Nano Mission has also facilitated national dialogues to promote R&D in nanotechnology standards development and the development of a regulatory framework roadmap for nanotechnology – National Regulatory Framework Road-Map for Nanotechnology (NRFR-Nanotech) (PIB, 2014).

Table 13: Initiatives undertaken for human resource development under the Nano Mission

Initiative	Intent	Examples
Fellowships and Awards	To encourage and provide opportunities for scientists to work on frontier technologies; train at international institutes; intensify research in their host institutes, and create expertise at the national S&T laboratories.	− BOYSCAST (Better Opportunities for Young Scientists in Chosen Areas of Science and Technology) fellowships granted to young nano-scientists for a duration of 3-12 months − Two National Nano awards instituted to be given to outstanding scientists in this field. − Ramanna Fellowship − Post-Doctoral Fellowships granted to nano scientists; anchored by JNCASR, Bangalore.
Advanced schools	To train researchers and generating the opportunity for them to develop hands-on experience on sophisticated techniques, instruments, and methods.	6 Advanced Schools organized on, − Nanomaterials Preparation, Characterization, and Manipulation, Bengaluru (2003) − Science of Size Reduction, Different Routes of Preparation, Characterization of Nanomaterials and Applications, Kolkata (2005) − Nanoscience and Nanobiology, Bengaluru (2007)

		− Science of Size Reduction, Different Routes of Preparation and Characterization of Nanomaterials and Applications, Kolkata (2009) − Nanoscience and Nanobiology, Bengaluru (2011) − Advanced School on Nanobiotechnology, Thanjavur (2013)
Organising and supporting Conference, workshops	Networking, information exchange amongst national and international scientists; to keep abreast of latest developments in the field identify mutual topics of interest and develop collaborative programs	− 6 International conferences on various aspects of Nanotechnology (ICONSATs) in 2003, 2006, 2008, 2010, 2012 and 2014 − 4 National Review and Coordination meetings in 2005, 2007, 2009 and 2011 to take stock of the R&D in India and evolve future directions − 2 Nano India Meets and 2 Group Monitoring Meetings in 2013 and 2015 to review the progress made in the supported projects
Post-Graduate Teaching Programs (M.Sc./M.Tech.)	To develop skilled researchers who can work in interdisciplinary environments	− Grant eligible to public institutions that possess the necessary teaching and lab infrastructure.

Source: Compiled by the author based on information available from the Nano Mission website (http://nanomission.gov.in)

6.3 Bilateral/Multilateral research collaboration

International collaborations in nanotechnology R&D is also gaining prominence in the various Indian S&T cooperation agreements. There are several mutual collaborations that have emerged in nanotechnology agreements between India and other countries (See, **Figure 9**). International collaboration is another objective of the Nano Mission. Under the Nano Mission, it is envisaged in the form of scientists' visits, joint workshops, conferences, joint research projects, access to research facilities abroad and joint centres of excellence. The period under the NSTI witnessed several initiatives under the sphere of international collaborations. Several bilateral research collaborations emerged in nanotechnology, as it was a part of nearly all the science and technology agreements between India and other countries. Joint R&D initiatives have figured prominently with Indian institutes engaging in research projects of a similar kind in the US, EU, Japan, Russia and Taiwan. These have largely focused on carbon nanotubes, functional nanocomposites, etc. Several joint meetings and workshops/conferences have also been held. Other actions include S&T initiatives with Indian diaspora – Scientists and Technologists of Indian Origin Abroad (STIOs) for encouraging networking between scientists and technologists of Indian origin that are based abroad and Indian scientists.[11] Under the NSTM, developing joint R&D, projects, scientific visits and conferences are being planned. Mechanisms for accessing sophisticated research facilities and forging academia-industry partnerships' at an international level are also are being developed.

The Euro-India Net is a forum set up under the Framework Programme (FP6) between EU and India to encourage collaborations in nanotechnology between scientists from the two regions. The forum seeks to examine and understand the policies and mechanism through which innovation and R&D is being developed in nanotechnology in India and the EU. Insights drawn will be used to strengthen ties between the two regions in nanotechnology within the domains of research, industry and governments.[12] The project, coordinated by Sociedade Portuguesa de Inovação (SPI), Portugal is being conducted by a number of prestigious institutions in addition to the coordinator SPI, Portugal including: Institute of Nanotechnology, UK; Malsch TechnoValuation, The Netherlands; Indian Institute of Science, India; Science and Technology Park, Pune; IIT Bombay; and, University of Delhi.

CSIR's International Science and Technology Directorate (ISAD) that aims to strengthen collaboration between CSIR and international institutes has facilitated workshops and collaborative projects with partners in countries like South Africa, France, Japan, South

[11] Nanoelectronics & nanodevices theme recognized at Session on "Creating Technology Corridors with STIOs" at 2nd Pravasi Bhartiya Divas (PBD) held in New Delhi during January 2003.

[12] http://nanomission.gov.in/

Korea, China, in the area of nanotechnology.[13] A joint Indo-France Symposium on Nanotechnology held in 2006 enabled discussions on basic nanotechnology research such as synthesis, characterization, etc., as well as its application in areas like medicine, agriculture, environment, textiles and industries.

Other international collaborations for nanotechnology where the government has played an active role include Indo-US S&T Forum, Indo-US High Technology Cooperation Group (HTCG), Indo-German Committee on Science & Technology, Program of Cooperation in Science and Technology; Indo-French Laboratory for Solid State Chemistry (IFLaSC). In the bilateral discussion between India and UK in 2009, research collaborations were identified in the areas of thin film performance, photovoltaic (PV) power systems and distribution, low-cost materials for PV cells, cost-effective isolated PV systems, and solar cells with a focus on cost reduction.[14] A memorandum of understanding was also signed between India and UNESCO in 2006 to establish a Regional Centre for Education and Training in Biotechnology, where one of the thrust areas is on nano-biotechnology. The Centre, which is now operational from 2009, aims at integrating science, engineering, and medicine to enable novel and economical solutions in agriculture, health, environment and energy resources besides generating skilled manpower in these areas. The Centre aims to promote and strengthen both South-North and South-South cooperation in the area of biotechnology around issues relevant to education, training, research and innovation, commercialization and trade and promote a web of satellite centres in these sub-regions.[15]

There are also regional networks promoting transnational cooperation on nanotechnology research and education. Asian Nanoscience and Nanotechnology Association (ANNA) in Japan is one amongst them having an ANNA Chapter on India. ICPC Nanonet, a web network created under the European Union funded project, provides a platform for knowledge sharing and forging collaborations between scientists in the EU and the

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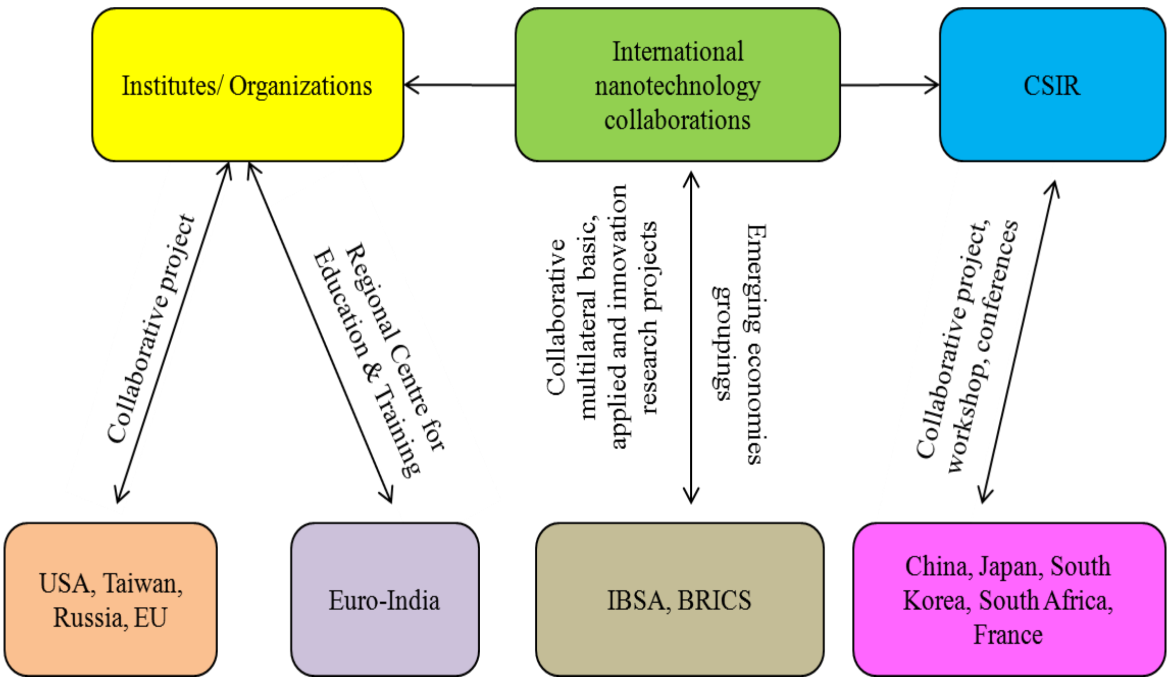
[13] http://www.csir.res.in/

[14] http://www.dst.gov.in/index.htm

[15] http://www.rcb.res.in/

International Cooperation Partner Countries (ICPC) of China, India, Russia, and Africa. The network provides open access to an electronic archive of published research in nanotechnology (Nano Archive) and organizes webinars on topics concerning nanotechnology.

Figure 9: India's international collaboration in nanotechnology



Source: Author

There also exists South–South Cooperation on nanotechnology. The IBSA Nanotechnology Initiative, launched jointly by the partnering nations of India, Brazil, and South Africa in 2005, envisages formulation of a mega-collaborative programme in areas of mutual interests like advanced materials, sensors, energy systems, catalysis, health (TB, malaria, and HIV), agriculture, water treatment and environment ("IBSA Nanotechnology Initiative – India, Brazil, South Africa" 2010). Over the years, the IBSA nanotechnology initiative has stimulated a variety of joint research projects and has adopted a development-oriented agenda. Broadly focusing in the areas of advanced materials, energy, human development, and health and water, IBSA has stimulated collaborative research projects on sensors, thin films and nanodevices, nanostructured organic and inorganic hybrid solar cells, nanotechnology based drug delivery systems, water purification systems as well as mechanisms to strengthen human resource development in the nano-domain. India leads its flagship project on water purification.[16]

Another prominent South-South collaboration in nanotechnology research is among BRICS member countries of Brazil, Russia, India, China and South Africa. The BRICS Thematic Leadership Program in Nanotechnology which is included in the Moscow Declaration and BRICS Science, Technology and Innovation Work Plan 2015-2018, is being coordinated by India. The focus areas of collaborative research include materials for power engineering, nanostructured materials and magnetic materials.[17]

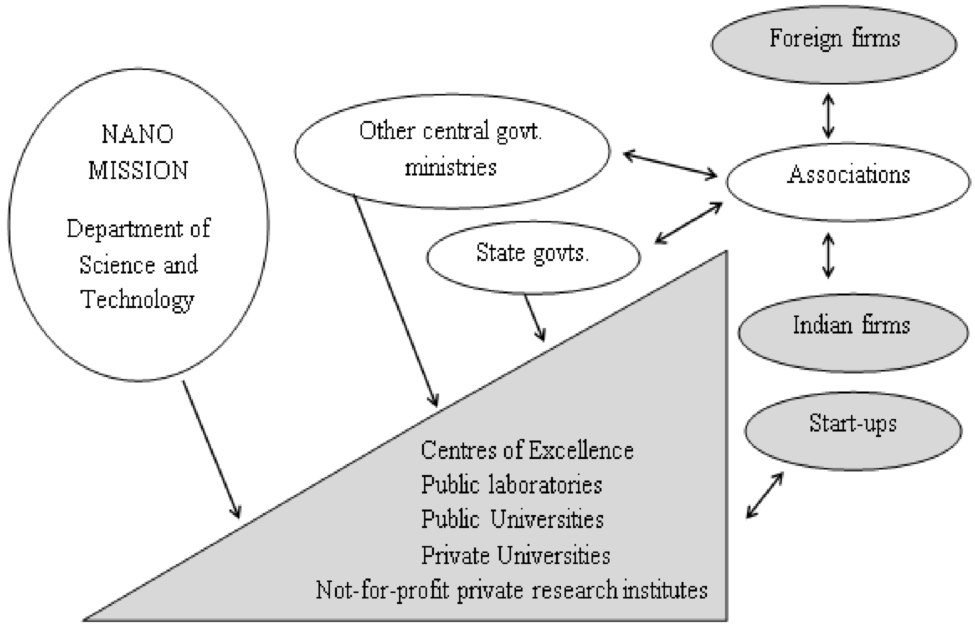
7. Conclusion

The key actor-network structure with respect to the emerging nanotechnology in India can be represented as in **Figure 10**.

The Indian government's S&T push in this emerging field acted as the main motor of capacity building. Despite the relatively smaller investment of the Indian state, resource mobilization has resulted in a substantial expansion in the knowledge base on nanotechnology. Public investment in new-knowledge absorption has had a high impact, only because the Indian scientific establishments already possessed the required knowledge necessary to learn about new emerging sciences. The expansion in the knowledge base in universities and public laboratories has given rise to a few start-ups and has resulted in some technology transfer to established firms. The activities of start-ups and large firms which have incorporated nanotechnology based processes in their production systems is yet to gain momentum in terms of generating products and services, despite the hype about nanotechnology.

[16] http://www.ibsa-nano.igcar.gov.in
[17] http://nias.res.in/BRICS/brics.html

Figure 10: Key actor-network structure of emerging nanotechnology in India



Source: Anand (2014)

In nanotechnology, the government programmes and polices aimed at fostering research and innovation activities could be categorized under the following:

Supply policies: To stimulate innovation generation in nanotechnology, the central government provided R&D grants and incentives for undertaking for a consortium of firms and research institutes besides creating centres of excellence in nanotechnology in select S&T establishments.

Diffusion policies: Development of IPR related policies have been undertaken to stimulate patenting and to enable commercialization of research products. Further, the creation of technology transfer offices to support in the patent application process, licensing agreements, search for partners and funding sources have recently been started mostly in institutes of national importance and in some universities/deemed universities.

Infrastructure policies: Academia-industry linkages can be further shaped by the government by developing science parks, research parks or innovation parks in the vicinity of S&T institutes. Development of such parks has recently been promoted by government schemes in some of the S&T institutes in India. These parks are intended to create clusters and often include business incubators to support spin-off and start-up companies.

Human resource policies: Education and training in the field of integrative and inter-disciplinary areas of science and engineering have been encouraged by enacting policies to generate skilled quality human resources and better respond to industry needs.

Policy thrust, which was initially oriented more towards building human capacity and infrastructure creation, has witnessed a shift in the recent years and is now directed towards product development and commercialization.

Regarding impact of global economic crisis on innovation, evidence shows that emerging countries, including India, has gained opportunities to demonstrate strengths in research and innovation (OECD, 2012). This also holds true in the case of nanotechnology in India. Despite the relatively smaller investment of the Indian state, a substantial expansion in the knowledge base on nanotechnology is observed. India's performance in nanotechnology in this regard is noteworthy. It has fared well in terms of the creation of scientific capabilities as demonstrated by the sizeable generation of scientific publications. Although the academic output in nanotechnology is growing, related patents and products are not always progressing at the same pace.

Analysis indicates the development of scientific capabilities and the potential of India to be an important player in this emerging field. But this opportunity may or may not materialise. The ability to take advantage of early scientific opportunities would be contingent on their ability to leverage their capabilities – including knowledge, governance, and financial structure – either through collaboration, alliances, ability to attract venture capital, foreign talent or through their downstream marketing capabilities.

To conclude, the paper provides insights into the capacity building process that marked the emergence of the nanotechnology research and innovation activities in India. The nanotechnology trajectory in India has also largely been shaped by policymakers. It is suggested that, through collective action relevant actors might well be able to substantially shape and coordinate the build-up process of an emerging technological field, and that collaboration in formal networks can be a crucial means in this regard.

Towards this, there is a need to incorporate a wider set of actors such as global, informal, user and social. Also, instead of focusing on the firm as a driving force, a focus on non-firm actors such as the community of practice, user, public sector, and the individual is important to effectively harness the potential of emerging technologies in the context of developing countries like India. Furthermore, the influence of cross-border international research and innovation linkages suggest that national policies on science, technology, and innovation also need to be international in orientation.

References

Aguirre-Bastos, C. (2010). Capacity building for innovation and sector systems of innovation - the case of renewable energy technologies and nanotechnology in Brazil, India, China, South Africa and Mexico (BICSAM). Austrian Institute of Technology Foresight & Policy development Department (AIT-F&PD) Report, Vol. 17, March 2010, p. 244

Allen, T.J. (1977). *Managing the flow of technology*, Cambridge: MIT Press.

Anand, M. (2014). Nanoscience and nanotechnology: the new sunrise industry? In S.V. Ramani (Ed.), *Innovation in India: combining economic growth with inclusive development*. Delhi: Cambridge University Press, pp. 211-241.

Attewell, P. (1992). Technology diffusion and organizational learning: the case of business computing, *Organization Science*, 3(1): 1-19.

BCC (2010). Nanotechnology: A Realistic Market Assessment, BCC Research, July. Available at, http://www.bccresearch.com/market-research/nanotechnology/nanotechnology-realistic-market-assessment-nan031d.html

Bhattacharya, S., Shilpa, and A.P. Jayanthi (2012a). Nanotechnology research and innovation in india: drawing insights from bibliometric and innovation indicators, CSIR-NISTADS Strategy Paper II, July 2012, NISTADS: India. Available at, http://www.nistads.res.in/images/bulletin/nano2.pdf

Bhattacharya, S., Shilpa, and M. Bhati (2012b). China and India: the two new players in the nanotechnology race, *Scientometrics*, 93(1): 59-87.

Burt, R.S. (1992). *Structural holes: the social structure of competition*, Cambridge: Harvard University Press.

Chandrashekar, S. and K.P. Basavarasappa (2001). Technological innovation and economic development: choice and challenges for India, *Economic and Political Weekly*, 36(34): 3239-3245.

Datta, S. and M. Saad (2011). University and innovation systems – the case of India, *Science and Public Policy*, 38(1): 7-17.

DST (2013). Research and Development Statistics 2011-12, Department of Science & Technology (DST), Government of India. Available at, http://nstmis-dst.org/rndstat-2011-2012/contents.pdf

Gupta, V.K. (2009). Indian patents output in nanotechnology, *Journal of Intellectual Property Rights*, 14(2): 164-165.

Huang, C., A. Notten, and N. Rasters (2004). Nanoscience and nanotechnology in Europe: analysis of publications and patent applications including comparisons with the United States, *Nanotechnology Law & Business,* 1: 1-19.

Hullmann, A. (2006). The economic development of nanotechnology – An indicator based analysis, Working paper, DG Research, European Commission, Brussels. Available at, http://www.umic.pt/images/stories/publicacoes/nanoarticle_hullmann_nov2006.pdf

Iansiti, M. and I. West (1997). Technology integration: turning great research into great products, *Harvard Business Review* (May-June), pp. 69-79.

Kogut, B. (1991). The permeability of borders and the speed of learning among countries. In T. Dunning, B. Kogut, M. Blomstron (Eds.), *Globalization of firms and the competitiveness of nations*. Lund: Lund University Press, pp.59-90.

Kostoff, R.N., R.G. Koytcheff, and C.G.Y. Lau (2007). Global nanotechnology research metrics, *Scientometrics*, 70: 565-601.

Krishnan, R.T. (2006). Barriers to innovation and the creation of a knowledge society in India, IIM Bangalore Research Paper - 243.

Lundvall, B.-Å. (1992). *National systems of innovation: towards a theory of innovation and interactive learning*, London: Frances Pinter Publishers.

Meyer, M., I. Makar, I. Rafols, D. Olsen, V. Wagner, A. Zweck, A. Porter, and J. Youtie (2008). EURONANO: Nanotechnology in Europe: assessment of the current state, opportunities, challenges and socio-economic impact (phase 1), final report. Sevilla: IPTS.

Mitra, R.M. (2007). India's Emergence as a Global R&D Center, Working Paper: R2007: 012, Swedish Institute for Growth Policy Studies, Stockholm. Available at, http://www.tillvaxtanalys.se/download/18.1af15a1f152a3475a818b69/1454505971336/India%E2%80%99s+Emergence+as+a+Global+R%26D+Center-07.pdf

Niosi, J. and S.E. Reid (2007). Biotechnology and nanotechnology: science-based enabling technologies as windows of opportunity for LDCs?, *World Development*, 35(3): 426-438.

OECD (2012). *OECD Science, Technology and Industry Outlook*, Organisation for Economic Cooperation and Development, Paris.

PIB (2014). Continuation of the Mission on Nano Science and Technology in the 12th Plan Period, Press Information Bureau (PIB), 20 February. Available at, http://pib.nic.in/newsite/PrintRelease.aspx?relid=103969

Ramani, S.V., N. Chowdhury, R. Coronini, and S. Reid (2010). On India's plunge into nanotechnology: what are good ways to catch-up? GLOBELICS Conference Proceedings, Kuala Lumpur, Malaysia, October, Available at, http://umconference.um.edu.my/upload/43-1/papers/189%20ShyamaRamani_NupurChowdhury_RogerCoronini_SusanReid.pdf

Reid, S.E. and J. Pliniussen (2002). The technological antecedents of nanotechnology, IEEE Engineering Management Conference Proceedings, Cambridge University, UK, August.

RNCOS (2015). Global Nanotechnology Market Outlook 2022, RNCOS, December. Available at, http://www.rncos.com/Market-Analysis-Reports/Global-Nanotechnology-Market-Outlook-2022-IM801.htm

Roco, M.C., C.A. Mirkin, and M.C. Hersam (2010). WTEC Panel Report on Nanotechnology Research Directions for Societal Needs in 2020. Retrospective and Outlook: WTEC.

Rogers, E.M. (1983). *Diffusion of innovations*, 3rd ed., New York: The Free Press.

Salerno, M., P. Landoni, and R. Verganti (2008). Designing foresight studies for Nanoscience and Nanotechnology (NST) future developments, *Technological Forecasting and Social Change*, 75: 1202-1223.

Sorenson, O. and T.E. Stuart (2001). Syndication networks and the spatial distribution of venture capital investments, *American Journal of Sociology*, 106(6): 1546-1588.