



Nanotechnology Research, Innovation and Commercialisation in India: Contemporary Status



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ISTIP (Indian S&T and Innovation Policy): First Study of its kind focusing on various dimensions of innovation activity in India; aiming at providing valuable inputs for S&T and Innovation decision making.

Contents

- Introduction
 - Stakeholders in Nanotechnology Research and Innovation
 - Promising Strategies for Research and Innovation in Nanotechnology
 - Research and Patenting Trends in Nanotechnology
 - Nanotechnology Industrial Involvement
 - Nano-Enabled Products
 - Nanotechnology Risk and Regulation
 - Final Remarks and Policy Implications
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This Policy Bulletin has been prepared under ISTIP project by Sujit Bhattacharya (Principal Author)^{1,2}, Shilpa^{1,2}, Preeti¹ and Umang Gupta². Authors are affiliated to CSIR-NISTADS¹ and AcSIR².

Introduction

Successful translational research is an outcome of various strategies, policies, developing institutional mechanisms, and support for scaling research from laboratory to a stage where it can be commercially exploited. It has been argued that strong connectivity between academia, industry and market leads to successful translation. Science-based technologies are driving innovation in the 21st century. Research in these emerging fields have become more strategic with funding directed towards research that can address industrial problems and technological uncertainties and can lead to more novel products or processes. Industrial research and industry sponsored research to academia sometimes exceeds public funding in these emerging fields. This type of research environment is visible in advanced OECD countries and leads to active academia-industry partnership and startups emerging from academia. In developing countries like India, research is primarily public driven initiative; industrial research funding is estimated to be only 20% to 30% of the overall research funding. Thus it becomes a challenge for developing countries to create an enabling environment that can exploit research leading to successful translation.

Nanotechnology is a science-based technology and promises to emerge as a key driver for future innovations across different sectors. Scientific and technological uncertainties are immense and downstream end of the innovation value chain is contingent upon addressing the upstream challenges and market uncertainty. New nano-materials for example on one hand exhibits promising possibilities but on the other hand requires extensive efforts for translation as a viable enabling material for enhancing product properties.

India like OECD and other emerging economies has made nanotechnology a 'priority' area, articulating

dedicated programs for building research and innovation capacity. It looks upon nanotechnology as a ‘window of opportunity’ that can have significant impact across different industries and also address developmental challenges.

India’s public driven efforts have resulted in the creation of research infrastructure in different academic and research centers, and research outcomes when measured through research publications are impressive¹. Invention and innovation driven activities/translational research however, has shown only a few successful outcomes. Indian patenting activity has been insignificant in comparison with other active players in this field. A few patents however, are promising and have been successfully exploited. Similarly, some promising applications are visible but large gap can be seen between promising research coming from laboratories and translation to useful processes/products. More dedicated efforts are required to address issues of EHS/ELSI (Environment Health Safety/Ethical Legal Societal Issues), and standardisation².

The important question now being asked is whether the initial promise shown by Indian research activity in nanotechnology can translate into useful economic and social outcomes³. A more informed exercise is thus required to underscore the research that has happened in terms of potentiality for exploitation. We need to ask: What challenges are required to be met for successful innovation and commercialisation? What types of patents have been developed? Do we observe emergence of patenting activity in some key application areas? Do we see industry involvement in nanotechnology? What types of processes and products have come out? *Overall we need to assess whether India is developing competency in some domains of nanotechnology and whether some promising signs of translation are visible.*

We argue that India has to exploit nanotechnology research for enhancing their industrial competency as well as address developmental challenges. Providing novel solutions for clean drinking water, mitigating unmet health needs, environmental remediation are more pertinent for developing countries like India wherein these problems are acute. *The policy bulletin underscores India’s nanotechnology development by examining whether it is leading towards developing industrial competency and addressing developmental challenges. We also identify promising policy initiatives that we argue need to be strengthened further and articulate policy interventions that can contribute towards responsible nanotechnology development.*

¹Bhattacharya, S., Jayanthi, A. P., Shilpa, Bhati, M. (2012). *Knowledge creation and innovation in nanotechnology: Contemporary and emerging scenario in India*. Prepared by National Institute of Science Technology and Development Studies. (Website link - <http://www.nistads.res.in/> under reports)

²Jayanthi, A.P., Beumer, K., Bhattacharya, S. (2012). Nanotechnology ‘Risk Governance’ in India. *Economic & Political Weekly*, xlvii (4), 34-40.

³Beumer, K., Bhattacharya, S. (2013). Emerging Technologies in India: Developments, Debates and Silences about Nanotechnology. *Science and Public Policy*, 40, 628–643.

Stakeholders in Nanotechnology Research and Innovation

India's involvement in high technology areas can be traced to policy formulation in the Sixth Five-Year plan (1980-85), with the launch of the programme for the Intensification of Research in High Priorities Areas (IRHPA)². From this period onwards, we observe Government of India (GoI) articulating dedicated mission mode programmes in high technology areas. In 2000, five government departments DRDO (Defence Research and Development Organisation), DST (Department of Science and Technology), CSIR (Council of Scientific and Industrial Research) and DeitY (Department of Electronics and Information Technology) - initiated a six year National Programme on Smart Materials⁴ (NPSM). This helped to draw country's attention towards the need for creating an enabling environment for research and innovation in smart materials and micro-electromechanical systems (MEMS). Areas covered under this program for development of smart materials and MEMS included aerospace, communication, automotive electronics, health monitoring, healthcare and entertainment. In the Tenth plan period (2002-2007), nanotechnology was identified as a priority area and a mission mode programme NSTI (Nano Science and Technology Initiative) was started. This umbrella programme was articulated and supported by DST. Other departments, prominent among them DeitY initiated dedicated programme in nano-electronics. In the eleventh plan period (2007-2012) 'Nano Mission', was launched which was a follow up of NSTI with the objective to strengthen capacities created through NSTI. The programme was also enlarged with new initiatives to involve larger number of institutions across the country in nanotechnology activity, dedicated support for promoting nanotechnology interventions in different sectors, initiatives to bring in other stakeholders with the motive of exploiting research.

Nanotechnology has now evolved as a multi-agency activity. Apart from DST and DeitY, other government ministries/departments are now promoting nanotechnology through domain specific programmes. Defence Research and Development Organisation (DRDO), Department of Biotechnology (DBT), Indian Council of Agricultural Research (ICAR) are some of the institutions where nanotechnology is emerging as an important research area for promotion. CSIR (different laboratories under it), Indian Institutes of Technology (IIT's), Indian Institute of Science (IISc), Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) and Indian Association for the Cultivation of Science (IACS) are some of the major research entities that have dedicated research programmes and groups involved in nanotechnology research. Some state governments have also initiated dedicated programmes for nanotechnology development.

²Jayanthi, A.P., Beumer, K., Bhattacharya, S. (2012). Nanotechnology 'Risk Governance' in India. *Economic & Political Weekly*, xlvii (4), 34-40.

⁴Kumar, A., Desai, P.N. (2015). Mapping the Indian nanotechnology innovation system. *World Journal of Science, Technology and Sustainable Development*, 11 (1), 53-65.

Apart from public institutions, other stakeholders, such as industry associations like Ahmedabad Textile Industry's Research Association (ATIRA), Confederation of Indian Industry (CII) are getting involved in nanotechnology. Some public sector undertaking, and some Indian and foreign firms are now actively involved in nanotechnology. A recent survey has estimated 300 firms visible in this area in India⁵. A few startups are emerging coming from university incubators. Thus, we see that stakeholders involved in Indian nanotechnology programme have become more enlarged and diverse. Particularly the involvement of industry and some of them developing linkages with academia is a promising sign.

Promising Strategies for Research and Innovation in Nanotechnology

In the last few years, one observes nanotechnology research in India getting more focused. One can now distinguish institutions involved in nanotechnology research in terms of broad areas of activity in this field. Emergence of research groups with domain capability and developing linkages with industry, more support available to them for advancing their research and research translating into potential applications are indications of developing research capability in nanotechnology.

We have identified two major initiatives by Indian government as important determinants in nanotechnology development: (a) Creation of Centers of Excellence (CoEs), and (b) Indian Nano Electronics User Program (INUP),

- CoEs have been created in different universities and research centers through funding provided by DST⁶ (under nanotechnology programme) and DeitY⁷. We have identified major role of CoEs in creating dedicated research infrastructure in different domains; developing domain specific research competency; developing public-private partnerships and providing an enabling environment for translational research. This is highlighted in the later section.
- Nanotechnology being highly capital intensive and interdisciplinary requires creation of advanced infrastructure. Availability of sophisticated instruments and competency to handle them is a major prerequisite for successful nanotechnology development. It is difficult to create this type of infrastructure in each institute. Key centers across the country which can provide access to researchers and students irrespective of their institutional affiliation is required for developing competency in this area. Creation of INUP is thus an important initiative in this direction. The programme developed by DeitY supports groups working in the area of 'nanoelectronics' through short, medium and long term projects. It provides access to facilities, hands-on training, and peer support to the scholars working at different locations.

⁵Indian nanotechnology industry directory by CKMNT, 2012

⁶CoEs created by DST are classified under three categories—Unit of nanotechnology, Center for nanotechnology, and Centre for computational materials science.

⁷CoEs created by DeitY are called Centre for Excellence in Nanoelectronics (CEN).

INUP also provides funding to universities and academia for using their facilities. It also organises workshops and seminars to disseminate knowledge and provides platform to scholars to collaborate and benefit from complementary expertise. Pilot study undertaken by the author's shows different institutes have received active support under this program. Among the finding of the pilot study was the need for expanding this programme to cover different locations across the country more effectively.

CoEs: Developing Capacity for Nanotechnology Research and Innovation

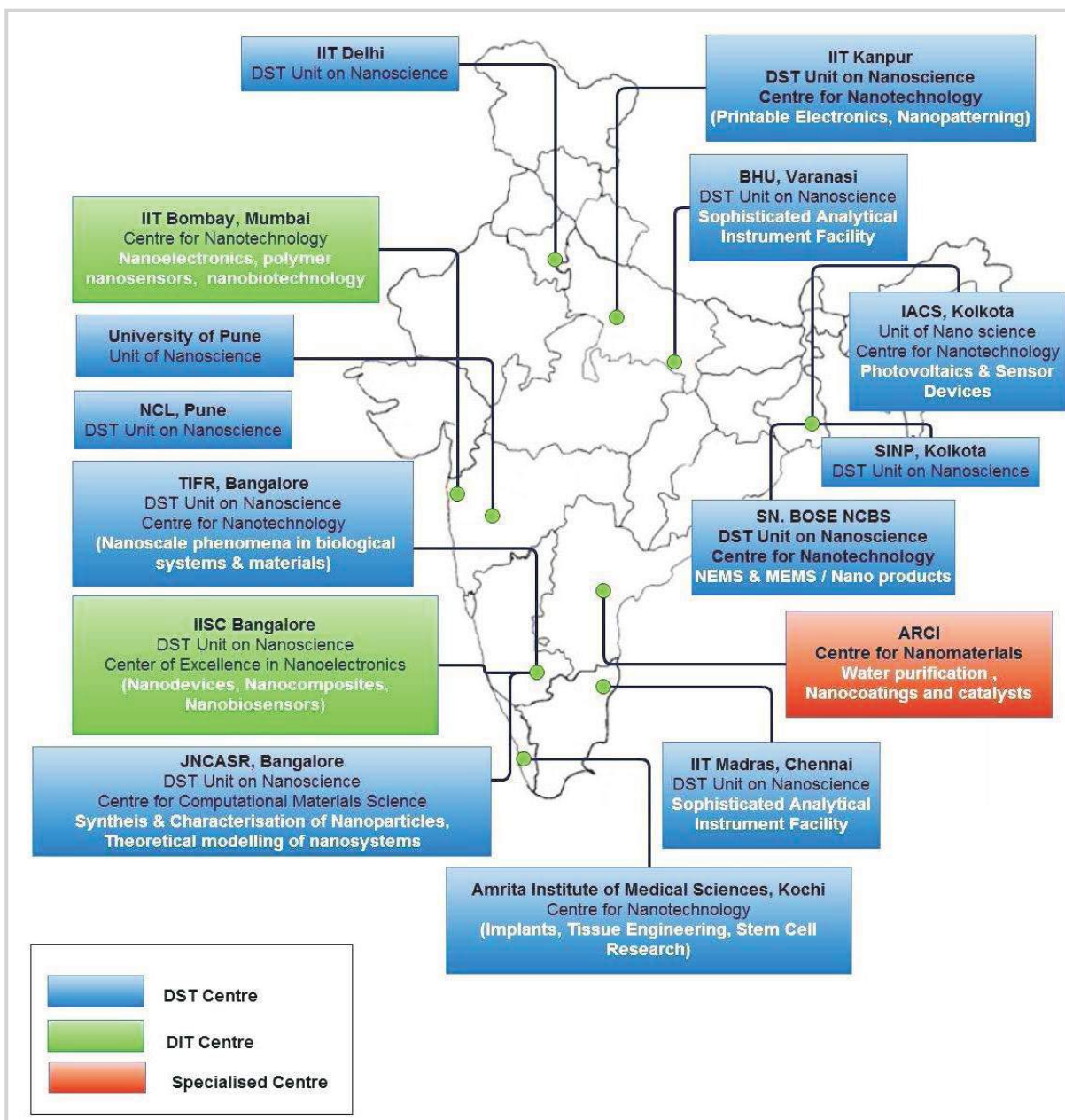
Centers of Excellence (CoEs) in specific nanotechnology domains have been created in institutions across the country. This policy action of creating CoEs addressing a specific domain has been guided by the overall research competency of an institute in that domain. The rationale has been to integrate nanotechnology research with the existing competency of that institute. Research activity in CoEs includes not only high technologies (like quantum transport, NMR in nano systems, electronics, and sensors) but also areas of developmental challenges (like water, energy, environment, health, security, cancer therapy). Most of these centers have access to sophisticated instruments and are developing capability to take forward research in the specific domains within nanotechnology. For example, CEN at IISc has created national nanofabrication center, MEMS and IC packaging facility, micro and nano characterisation facility and computational nanoengineering laboratory. This center has recently built a state-of-the-art nanofabrication facility 'Center for Nanoscience and Engineering' (CENSE). The creation of this center has helped to consolidate the activities undertaken by CEN at different departments and has provided access to various sophisticated instruments at a central location. Nanofabrication prototyping facility has been set up at IIT-Bombay to encourage SMEs for product development and commercialisation. IIT-Kanpur has developed facility for nano-materials preparation and characterisation. Instruments like pulse laser for thin-film deposition system, scanning electron microscope with e-beam lithography, and maskless photo-lithography are available for this purpose.

The issues that need attention is more aggressive strategy for developing linkages with industry. *Another drawback is that no CoE has been created in the area of EHS/ELSI.* CoEs are however, now making efforts for addressing EHS/ELSI concerns; for example Amrita Institute of Medical Sciences has developed a laboratory in nano-toxicology, International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) has undertaken lifecycle analysis of nanosilver based water filter developed by them for water disinfection⁸. EHS effect of nanosilver in the traditional ceramic water filter candles was examined and it was found that silver leaching out of freshly prepared candle filters was well within WHO limits for silver in drinking water.

Figure 1 highlights CoEs and CENs in different institutions across the country.

⁸Purushotham, H. (2012). Transfer of nanotechnologies from R&D institutions to SMEs in India: Opportunities and Challenges. *Tech Monitor*, Oct-Dec, 2012, 23-33

Figure 1 – Nanotechnology Centers of Excellence in India



Note - NCL-National Chemical Laboratory, TIFR-Tata Institute of Fundamental Research, IISc-Indian Institute of Science, JNCASR-Jawaharlal Nehru Centre for Advanced Scientific Research, BHU-Banaras Hindu University, SINP-Saha Institute of Nuclear Physics, ARCI-International Advanced Research Centre for Powder Metallurgy and New Materials, SN Bose NCBS-S. N. Bose National Centre for Basic Sciences.

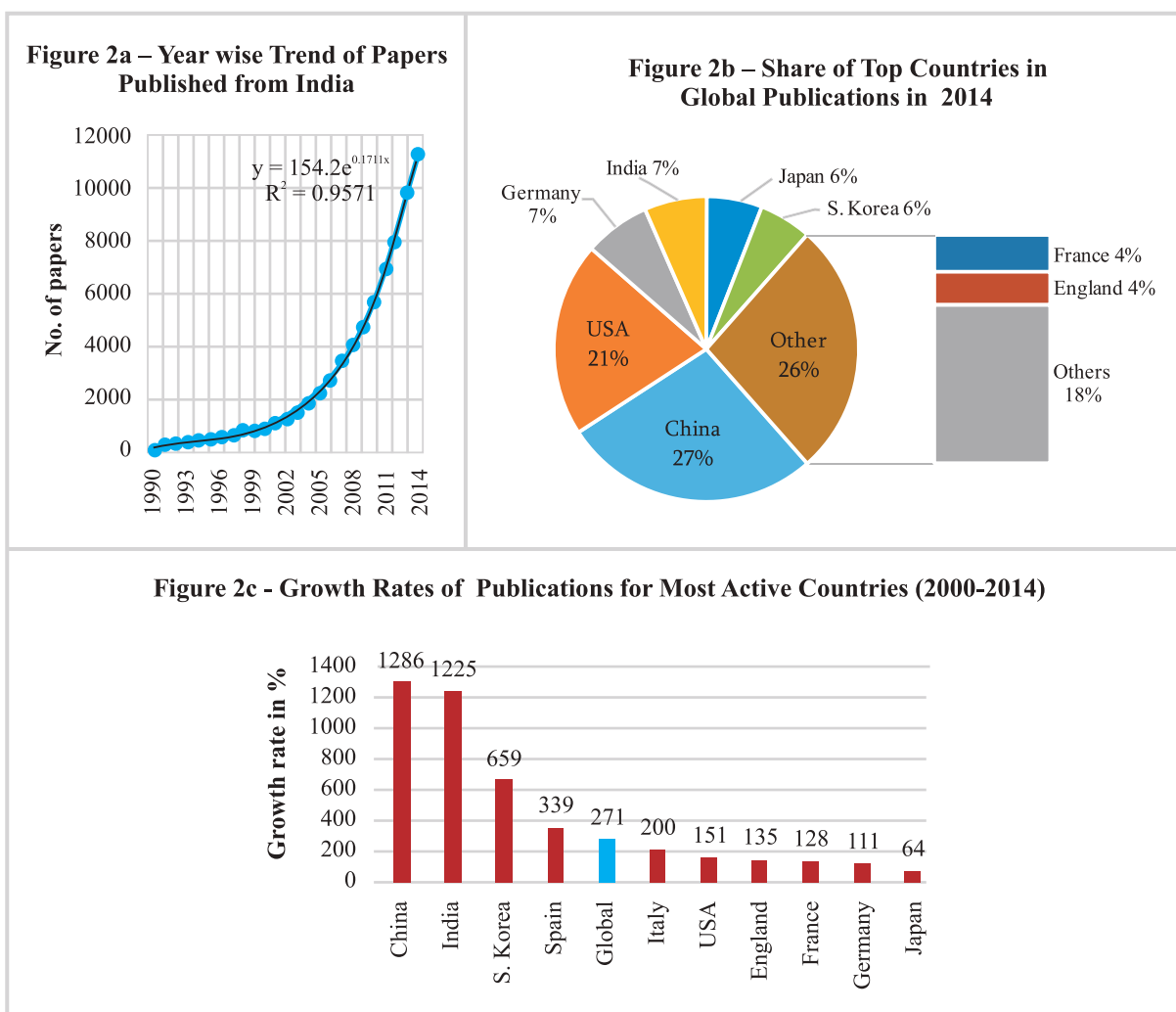
The two CoEs created by DeitY are in IIT-Mumbai and IISc. These CoEs are identified as CEN (Centre for Excellence in Nanoelectronics)

Research and Patenting Trends in Nanotechnology

Research Trends

Research publications particularly in science-based technologies provide important indication of research competency and to some extent the capability of creating innovation. India in 2014 became 4th in terms of publication productivity in nanotechnology. Figure 2 indicates India's publication trend and activity *vis-a-vis* some advanced and emerging countries

Figure 2 - Indian Publication: Trend and Global Positioning in Nanotechnology



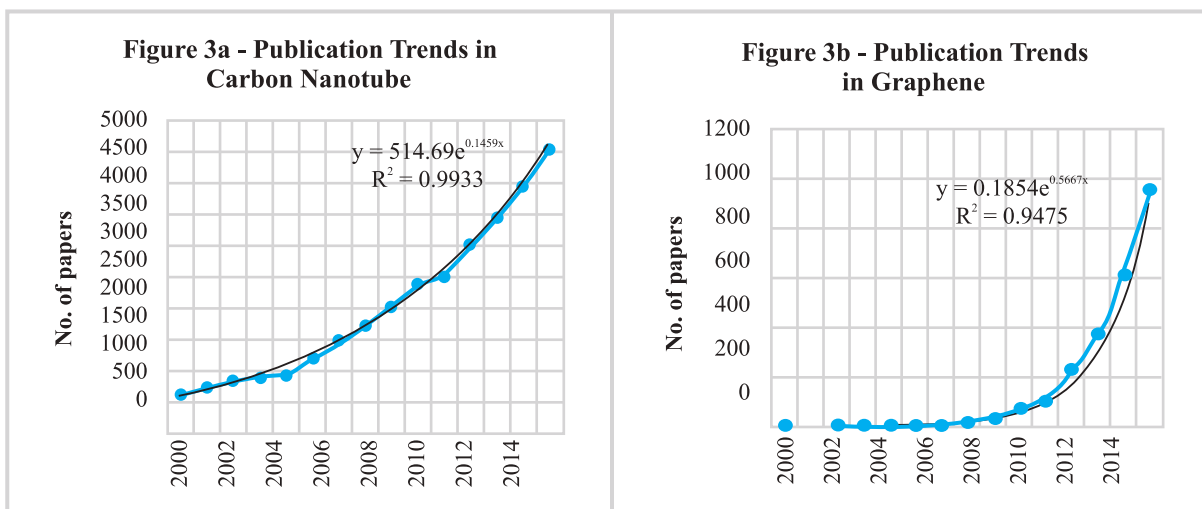
Source – SCI-E

Institutes involved in publication activity increased almost eight times during 2000 to 2014. Some of the prolific institutions in 2014 which were not visible in 2000 are Vellore Institute of Technology (178 papers), Tezpur University (118), Sastra University (118) and Alagappa University (80). Substantial research has been undertaken in many areas of developmental

challenges. For example, during 2010-2014 in ‘targeted drug delivery systems’ (India ranked 3rd globally; 2406 papers); water purification and management (3rd rank; 5494 papers); agriculture (3rd rank; 122 papers); environment sciences and engineering (4th rank; 653 papers). Research is also addressing high technology areas: applied biotechnology and microbiology (3rd rank; 1074 papers); biosensors (4th rank; 16223 papers), energy fuels (7th rank; 843 papers), solar research (7th rank; 2375 papers). However, it raises concern that toxicology (53 papers), an important area of nanotechnology research is exhibiting sparse activity. This research paper trend in toxicology is unlike what is being exhibited by countries active in nanotechnology research.

Nano-structures were primarily coming from carbon-based nanomaterials and inorganic nanomaterials (mainly silver, zinc-oxide, and titanium-oxide, gold). Extensive nanotechnology research was observed in development of new and improved nanomaterials, and improved processes of production. Nano-carbon family primarily carbon nanotube (CNT) and graphene are emerging as hot areas of research globally as well as in India. Carbon based nanomaterials cover almost 50% of total nanotechnology publications in 2014 from India. Comparisons among the total number of publications by the two carbon-based nanomaterials are illustrated in Figure 3. Close correspondence between CNT and graphene was observed as more than 50% of papers in graphene publications also include the term CNT.

Figure 3 - Indian Publication Trends in Carbon based Nanomaterials



Source – SCI-E

The publication increase in the period from 2000 to 2014 is around 600% (in case of CNT) and fits exponential growth trend. In case of graphene, research actively started from 2010 with strong exponential trend observed during the period 2010-2014 with publication increasing to approximately 800% from that in 2010.

Many of the laboratories of CSIR and IIT's are actively involved in CNT and graphene research. In 2014, CSIR produced 1215 papers and IIT's 1856 papers in CNT, and 224 papers and 163

papers in graphene respectively. Some other prolific institutions include IISc (178 papers in CNT, 61 papers in graphene), JNCASR (178 papers in CNT and 43 papers in graphene), and Banaras Hindu University (108 papers in CNT and 31 papers in graphene). Research is directed towards nanoelectronics, energy storage devices, bio-nanofluids for treatment of cancer hyperthermia, targeted drug delivery etc. Global attention recently came when a young research scholar from Allahabad University demonstrated a cheap, simple and time-saving method for synthesis of graphene⁹. This synthesis method doesn't require huge furnace and is environment friendly. This method is now being further developed through international collaboration to translate it to production process.

Nanomaterials possess unique properties with wide range of applications. However, the key challenge is to produce high quality nanomaterials at large scale and at low cost and in a responsible manner (addressing issues of EHS). This calls for refining existing methods and devising new methods for synthesis of nanomaterials at laboratory level. Table 1 highlights the different methods for production of nanomaterials and Indian research activity in these areas.

Table 1 - Indian Research Activity in Different Methods of Production of Nanomaterials

Methods	Characteristics	Indian Research Papers	
		2014	2010
Sol gel	High chemical homogeneity; low processing temperatures; controlled size and morphology of nanoparticles; contamination free; varied applications; production rate is very low	548	296
Epitaxial Growth	Nanomaterial produced can replace silicon; scalable but expensive; Toxic substances used during production through this method is a major constraint	173	173
Exfoliation Method	Large scale production and low cost of production; low yield makes this process not highly suitable for industrial production	134	64
Chemical Vapor Method	High quality and large scale production of nanomaterials; scalability is low and expensive	69	44
Physical vapor Deposition	Flexibility in usage of varied type of organic and inorganic materials for deposition and surface materials; high capital cost; high vacuum and high temperature required which is not user friendly	31	13
Arc Discharge	Large scale production of high quality graphene	8	12
Unzipping of CNT	High quality and low cost for graphene production; impure nanomaterials are produced which is a major constrain	6	-

Source - Research papers extracted from SCI-E; Characteristics drawn from various technical bulletins

⁹The Times of India, 5th July, 2012. Available at: <http://timesofindia.indiatimes.com/city/allahabad/Young-scientist-from-Allahabad-University-in-breakthrough-graphene-research/articleshow/14695444.cms>

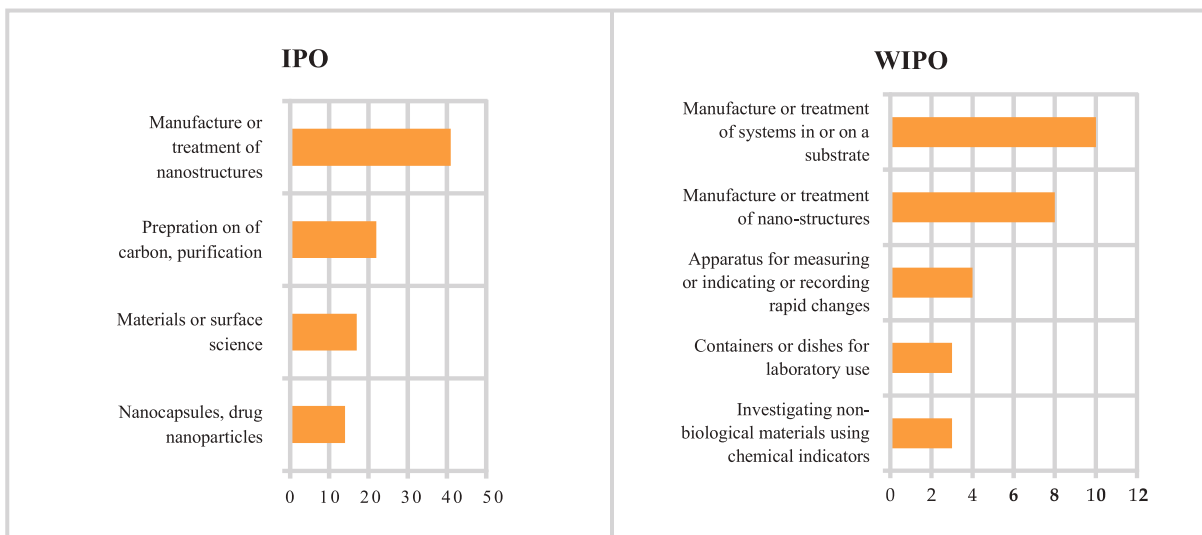
Table 1 provides a useful insight of the key methods of nanomaterial production, and strengths and weaknesses of each method. In some of the production methods, Indian research activity is visible, however more research attention is required in some new production methods.

Patenting Trends

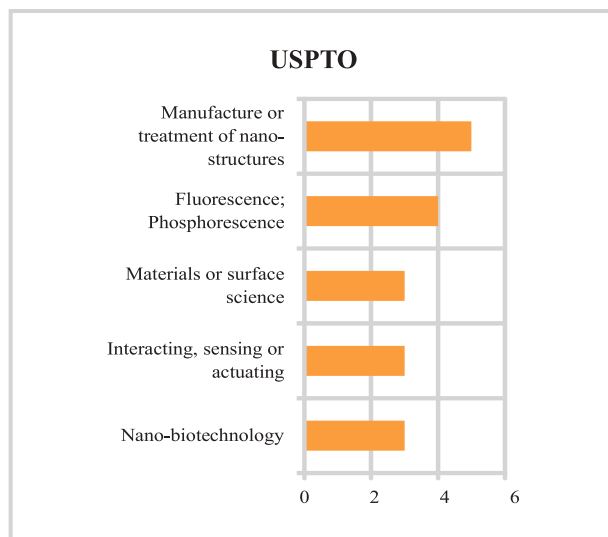
Indian assignees filed 50 patents in US Patent Office (USPTO), 57 through PCT (WIPO) and 117 patents in Indian Patent Office (IPO) during 2001-2014. Figure 4 gives further details of IPC classes¹⁰ where Indian assignees have filed patents in the three patent offices. ‘Treatment and manufacture of nanostructures’ is the dominant area of Indian patent application in all the three patent offices. ‘Preparation of carbon based nanomaterials’ is also an area of active patent filing in IPO. Another area of activity in IPO as well as in WIPO is ‘materials and surface sciences’. ‘Investigation of biological and non-biological material using chemical indicators or fluorescence’ also shows active patent filing in WIPO and USPTO. Some other visible classes of Indian patent filing are nano-biotechnology, drug delivery and sensing systems in these two patent offices.

Granular investigation was undertaken by examining title and claims of filed patents in the three patent offices. In IPO, major filings are in biomedical sciences, electronics, and environment. Patents filed under biomedical applications include treatment of cancer, ocular diseases, respiratory distress, nerve disorders, lung diseases, drug delivery systems, magnetic and fluorescent imaging, biosensors and bio-imaging. Patent filing is also active covering different sub-domains of energy primarily fuel cells, dye sensitized solar cells, sensors, semiconductor electronics, heat dissipation and electro-magnetic shielding. Water treatment, environment, pollution control, coatings, textiles and agriculture are some other visible application areas.

Figure 4 – Prolific IPC Classes of Indian Patents Filing in Three Patent Offices

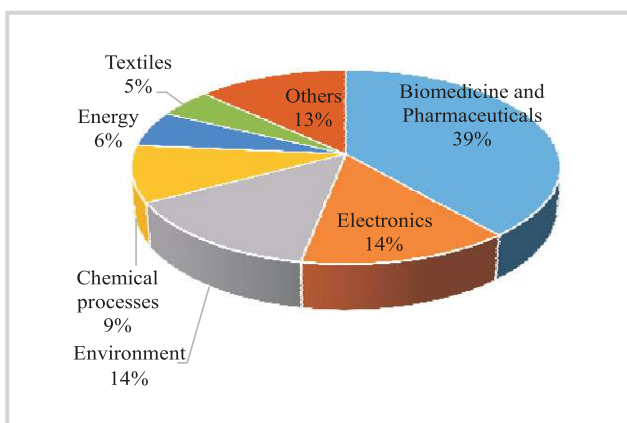


¹⁰International Patent Classification (IPC) provides a hierarchical system of symbols for the classification of patents according to the different areas of technology to which they pertain.



Source – Thomson Reuters Patent Database; *Horizontal Axis => Number of patents

Figure 5 - Areas under Patent filing in India



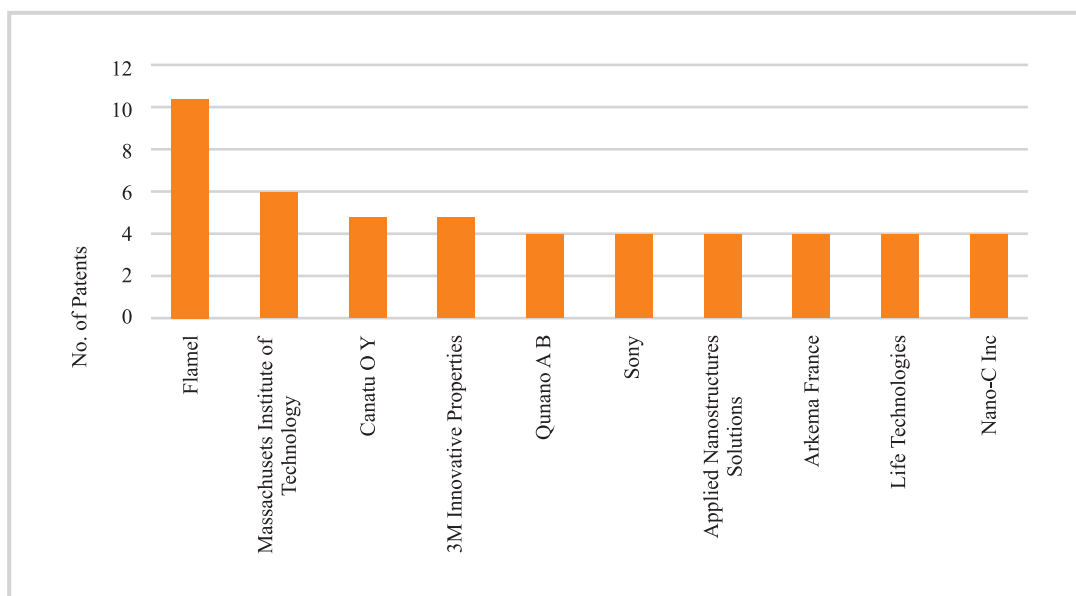
Source – Constructed by Authors

In USPTO, biomedicine is also an important area of filing. Patents filed cover nanotechnology based intervention in treatment of cancer, targeted delivery, genetic engineering, etc. Few patents are visible in energy applications and electronics. Applications using graphene as nanomaterial are also visible in USPTO. In WIPO, biomedical, drug delivery, energy, and electronics are other active areas of patent filing. Patents filing in the three patent offices are mainly by IIT's (15 in USPTO, 15 in WIPO, 26 in IPO) and CSIR laboratories (16 in USPTO, 26 in WIPO, 15 in IPO). Some other institutions involved in patent filing are DRDO (3 in USPTO, 5 in WIPO), IACS (2 in USPTO and WIPO, 7 in IPO) and IISc (2 in USPTO, 3 in WIPO, and 4 in IPO).

Around 200 foreign entities and 35 Indian entities have filed nanotechnology patents in IPO. Figure 6 highlights the foreign entities actively involved in patent filing in IPO. Dispersion of foreign filers in terms of their origin and activity areas can be observed: France based pharmaceutical company 'Flamel Technologies' followed by 'Massachusetts Institute of Technology' in USA, 'Canatu O Y' a Finland based company operating in electronic devices and gadgets, '3M Innovative Properties Company' from, USA a service provider in the area of intellectual property, 'Sony Corporation' from Japan working in electronics domain, 'Arkema France' working in the area of chemicals and advanced materials, and 'Nano-C Inc' from USA

working in the area of carbon based nanostructures, Qunano AB from Sweden working in the area of semiconductor and non-semiconductor nanowire technology with application in diverse fields.

Figure 6 – Prolific Foreign Entities Filing in India



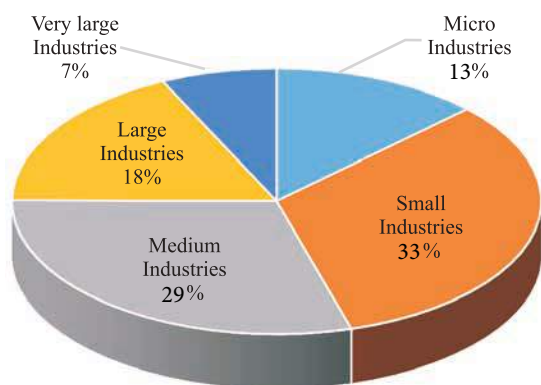
Source - Thomson Reuters Patent Database

Nanotechnology Industrial Involvement

A limited role of industrial firms in India is observed in exploration (research activity with research papers as a proxy indicator) and exploitation (patenting as a proxy indicator). Only 138 papers have been published with industry affiliation in 2014. These papers are from 101 firms involved in publishing activity. Most of these papers are published in collaboration with academia or research institutions. This to some extent is a promising sign as it is an indication of establishing academia-industry linkage. Industrial research is observed mainly in treatment of diseases like cancer, heart disorder, development of water treatment systems, improvement of lithium ion batteries using graphene. Some research activity is also visible in producing scalable and stable nanomaterials. Research papers are coming primarily from big pharmaceutical firms (for example Piramal Life Sciences, Dr Reddy's lab, Reliance Life Science), firms involved in water treatment (Manian Labs, Noritake cooperation, Lab4Life Biores), and those involved in energy studies (Amara Raja Batteries). Fifteen foreign multinational corporations are involved in publishing activity contributing total 22 papers in 2014. Some of these firms are WITEC GmbH, IBM, Noritake Cooperation, INTAS pharmaceuticals and Taiwan Semiconductor manufacturing. Collaboration is mainly happening with IIT's (30 papers).

A few firms are involved in patent filing. Only 1 patent is filed by industry in USPTO, 5 in PCT and 14 in IPO. These patents are coming from big firms from different sectors like Tata Chemicals, Tata Steel, Cadila Healthcare, Bharat Petroleum, and Hindustan Lever. *Only one patent in WIPO is filed in collaboration with academia involving Hindustan Petroleum, IIT-Delhi and Center for High Technology. This patent is in new process for the production of CNT.* Patents emerging from industry mirror the patenting focus of academia i.e. drug delivery for cancer treatment, coating materials, stable nanoparticles (aluminium phosphate) and sensors.

Figure 7 - Nanotechnology Firms in India (Size-wise Breakup)



Source – Authors construction from 'India Nanotechnology Industry Directory' (2012), Centre for Knowledge Management of Nanoscience & Technology; Note - Size-wise breakup is done on the basis of number of employees in a firm; Micro (less than 10), Small (11-100), Medium (101-1000), Large (1001-10000), Very large (above 10000)

Indian nanotechnology industry directory by CKMNT, 2012 has identified 300 firms operating in India in nanotechnology. They include both Indian and Foreign firms/multinational corporates. A wide dispersion is seen in terms of size and operation domain. Figure 7 highlights the distribution of firms based on employee size. Micro and small firms are basically involved in bulk production of nanomaterials. Large and medium firms are applying nanotechnology in their established product. For example, almost all the major pharmaceutical firms are active in exploring nanotechnology for drug delivery systems. Similarly all major paint companies are exploring nanomaterials applications to make efficient coatings.

The largest concentration of firms (about 19%) are in 'biomedicine and pharmaceuticals'. Almost all major pharmaceutical firms in India are exploring nanotechnology based interventions. One area of success has been in optimising drug delivery using nano-encapsulation. This has also been the major research domain in India and have shown tangible translational research. Another large concentration of firms comprising almost 15% are in coating materials. Nanotechnology enabled coating materials in which firms are involved range from coating on metal surfaces, fabrics, plastics, glass to adhesive coatings and paints. A number of firms are also involved in developing nanofabrics and textiles i.e. applying nanotechnology for enabling properties of wrinkle free, anti-bacterial fabrics, having good elasticity and strength, etc. One can also observe major textile Industry association ATIRA involvement in developing nano-fiber textile. The major public sector and private sector firms in petro-chemical sector

(Indian Oil Corporation, Bharat Petroleum, Hindustan Petroleum, Reliance Industries Ltd.) are also seen actively exploring nanotechnology based interventions. Other major sectors where nanotechnology firms are visible include manufacturing, industrial and laboratory chemicals, ceramic products, equipment and products like fertilizers, pesticides and machinery for agricultural purposes, healthcare and cosmetic products, and water treatment. Almost all major tyre companies in India (Ceat Tyres, JK tyres) are exploring nanotechnology based interventions for enhancing functional properties of tyres.

Majority of nanotechnology firms are located in Mumbai, Pune, Bangalore, Hyderabad, Ahmedabad, NCR and Kolkata. The presence of excellent universities and research centers seems to be a plausible driving factor for location of nanotechnology firms. This is unsurprising as this is a science based research area.

Nano-Enabled Products

The nanotechnology market can be classified in three segments: nanomaterials, nanotools and nanodevices. Of these, nanomaterial is the largest segment, accounting for 97.6% of global nanotechnology sales¹⁰. This segment includes the potential nanomaterials usage for product enhancement. India is also in the same league. Majority of applications available in Indian market are enabled products. Firms are using this technology to improve their existing products in the area of electronics, textiles, drug delivery systems, water treatment systems, etc. Table 2 highlights the technologies developed and institutions involved in their creation and development. Categories have been made more granular to draw more informed view.

Table 2 - Technologies Developed and Key Players in Different Application Areas of Nanotechnology

Application Areas	Technologies Developed in India	Key Players
Energy storage, production and conversion	Nano-sized lithium iron phosphate for making electrode for Li-ion batteries; Nano-ferro electric materials for microwave devices; Solar photovoltaic cell; Nanofluid inferometer; Nanofluid heat capacity apparatus; Lightning arrestor (varistor); Sensitive substrates for Raman Spectroscopy	IACS, IIT-Mumbai, IISc, IIT-Delhi, IIT-Kanpur, CSIR, SINP, Amrita University; Industria Nanotech, United Nanotechnology, NEI Corporation, Mittal Enterprises, Crane Software, Bharat Electronics, Moser Baer, Insta Power
Water treatment and remediation	Nano silver loading on ceramic water filter candle; CNT-based liquid flow sensors; Nano filtration plant; Aquaguard total water purifier	IIT-Madras, ARCI, IIT-Delhi, IIT-Kanpur, CSIR, Tata Chemicals, Eureka; SBP Aquatech, Eureka Forbes

Application Areas	Technologies Developed in India	Key Players
Disease diagnosis and screening	Hydrogel wound dressing; Nano blaster to blast cancer cells in human brains; Breast cancer nano drug; Cardiac diagnosis product; Nano sensorbased typhoid detection kit; Micro-diagnostic kit based on nanotechnology for TB	IACS, IIT-Mumbai, IISc, IIT-Delhi, IIT-Kanpur, CSIR, University of Delhi, Lifecare Innovations, <i>Velbionanotech</i> , Biocon
Drug delivery systems	Nano particles of inorganic compounds to form non-viral carriers; Bio-nanochips and DNA-based drugs; Nanoparticles loaded drugs; Nanotech-based drugs; Anti-counterfeiting technologies; Combination drug eluting stent; drugs to block cell proliferation in the narrowed diseased coronary arteries	IIT-Mumbai, IIT-Delhi, Prakruthik Health Care, Shasun Pharmaceuticals, Biochem, Bilcare, Natco Pharma, <i>Richmond Chemical Corporation</i> , <i>Vascular Concepts</i> , Dabur Pharma, Concept Medical Research, <i>Abraxis Bioscience</i> , Vitrus Techno Innovations, <i>Nano Development Corporation</i> , Biomix Network, Dr. Reddy's Laboratories
Textiles	Antibacterial clothing	IIT-Delhi, IISc, ARCI, Bodal Chemicals, Arvind Brands, Arrow, Raymond, Mohan Clothing, Ashima Bharati, Walmart, Max Titan Industries, Resil Chemicals
Automotive	Nanocomposite polymers, Carbon black-fumed silica for rubber, blends etc, Nono-Cu blend based Nano-lubes.	Appollo Tyres Ltd. Auto Fiber Craft, Ceat Ltd., Hindustan Petroleum Corporation Ltd., India Oil Corporation Ltd., Jk Tyres & Industries Ltd. Reliance Industries Ltd.

*Authors construction from various sources including websites and annual reports of research institutions and firms; Firms in Italics are Foreign MNCs.

Some targeted applications are also visible in other domains; for example, development of nono enabled explosive detector by a start-up 'Nanosniff technologies' at IIT-Mumbai that acts as a electronic nose by sniffing out explosives.

Nanotechnology Risk and Regulation

Nanotechnology innovation and commercialisation is now increasingly calling for risk assessment with a longer term goal of responsible technology development. Responsible technology development, EHS/ELSI has not found any specific mention in the nanotechnology policy articulations in India. Nanomission has funded a few projects in the area of risk research, however dedicated support is not visible. ICMR and CSIR are other key players involved in risk research. Recently, some initiatives have been taken for addressing risk issues by some institutions. ARCI undertook impact study of its nanosilver based water filter on environment, recycling, and life cycle analysis¹¹. Laboratories under CSIR primarily IITR, IICT, CFTRI, CDRI

¹¹Sarma, D. (2011). Life Cycle of a Nanosilver Based Candle Filter: Examining Issues of Toxicity, Risks, Challenges and Policy Implications. *Journal of Biomedical Technology*, 7, 83-84.

are involved in toxicity studies covering nanomaterials¹². IITR is investigating risks associated with nanomaterials partly through funding of DST and European Framework Program. An important outcome of their work is the development of a guidance document for safe handling of nanomaterials. National Institute of Pharmaceutical Education and Research is developing regulatory approval guidelines for nanotechnology based drugs and standards for toxicological tests in nano-based drug delivery systems¹³. ELSI issues also require more intense activity. It is restricted to only a few institutes in India. In 2010 government announced the establishment of regulatory board for nanotechnology. It is important that institutionalisation of this board takes shape.

One important issue that links to regulation is standard development. It is a great challenge to devise ways for standardisation in nanotechnology. Accurate measurement of the dimension including physical, chemical and mechanical properties of nanomaterials is highly complex activity because of their extremely small size and their minuscule response to any perturbation used to measure a property¹⁴. As a result, the reported properties of these materials vary widely from group to group. International Organisation for Standardisation (ISO) and the International Electrotechnical Commission (IEC) are two key international agencies in standard making. ISO and IEC have established Technical committee TC 229 and TC 113 respectively. European Union, USA, Japan, UK and China are actively involved in standard making.

Strategic collaboration among firms and countries and development of anticipatory standards is playing a key role in creating nanotechnology standards. Only in the latter stages of nanotechnology development in India, dedicated efforts are visible in standard creation and adoption. The Bureau of Indian Standards (BIS) coordinates the overall standardisation activity in India, and is the national standards authority. Only in 2010, BIS set up two sectional committees for nanotechnology standard: 1) MTD 33 for nanotechnology, which liaises with the corresponding international committees (ISO/TC229/WG2) on measurement and characterisation. Nano devices, sensors, transistors, initiators and atomic force microscopy have all been identified as priority areas by MTD 33. 2) MHD 21 for medical biotechnology, which deals in the ISO/TC229/ WG 3 on the health, safety and environmental aspects of nanotechnologies. So far two standards are at the test stage: National standard on use of atomic force microscope for characterisation and evaluation of nanomaterials, and electron microscopic characterisation of multi-wall carbon nanotubes. The remaining two standards proposed are: Luminescent nanomaterials and magnetic nanoparticles, and standard on toxicity of zinc-oxide

¹²IITR: Indian Institute of Toxicology Research; IICT: Indian Institute of Chemical Technology; CFTRI: Central Food Technological Research Institute; CDRI: Central Drug Research Institute.

¹³Jayanthi, A.P., Beumer, K., Bhattacharya, S. (2012). Nanotechnology: 'Risk Governance' in India. *Economic & Political Weekly*. xlvii (4), 34-40.

¹⁴Bhattacharya, S. (2015). Nanotechnology Standard Development (ed: Banerjee, P., Bhattacharya, S., Kumar, V., Mandal, K., Mehra, K., Pohit, S., Raina, R.S., Suman, S.). *India Science and Technology Volume 3* (pp. 341-345). New Delhi: Cambridge University Press.

nanomaterials. National Metrology Institute of India has designated responsibility to CSIR-National Physical Laboratory (CSIR-NPL) to formulate nanotechnology material standards. It has identified three areas for developing standards in nanotechnology: 1) Standardisation of magnetism in magnetic nanoparticles 2) Standardisation of optical emission from quantum dots, and 3) Process standardisation. NPL is member of ISO/TC229 and has also developed linkages with some international standardisation bodies. NPL is coordinating with BIS for developing national level standards and DST in defining nanotechnology regulatory framework. Another major player is DeitY that is helping in the creation of national facility for nano-metrology and standard development.

Final Remarks and Policy Implications

- Nanotechnology has evolved as a multi-agency activity. Major academic institutions and research organisations have articulated dedicated programs to create research competency in this field. Stakeholders are getting diverse with private players and some industry associations getting involved.
- In India, particularly in emerging technologies such as nanotechnology wherein university-industry partnership and translational research becomes key driver of innovation and commercialization, developing institutional arrangements that can promote linkages needs high priority.
- We have demonstrated the major role played by CoEs and INUP in developing research ecosystem in nanotechnology. CoEs in different domains are located in institutions across the country and have created domain specific competency in nanotechnology. Availability of sophisticated instruments and experts have created an environment where young researchers are trained in CoEs. However, only in a few CoEs we find dedicated research activity in risk research. However, there is no dedicated CoE in risk research. Dedicated focus is required for creating competence for adopting standards being developed in nanotechnology. However, global competency can only happen if new standards are being developed. This is also true for development of instruments as nanotechnology research and innovation is contingent upon availability of sophisticated instruments. It becomes extremely difficult to make available sophisticated instruments in multiple locations. This is another area which requires urgent attention. CoEs and INUP programmes have addressed this issue i.e. availability of sophisticated instruments to some extent. However, dedicated programme is required for instrumentation development in nanotechnology. Thus, we make a strong argument for creating CoEs in regulation, risk research and standard making and also in instrumentation development.
- INUP is situated at two places i.e. IISc-Bangalore and IIT-Mumbai. It has helped to create opportunities for researchers in nano-electronics domain. Many universities where nanotechnology activity is taking place is linking up and expanding their capabilities through INUP. There is urgent need to expand this program and situate INUP in other institutes across the country.

- Research publications provide good indication of India's research competency. India in 2014 was the 4th largest producer of research papers in nanotechnology as per SCI database. Indian research is addressing cutting edge technology areas (such as sensors, catalyst) as well as areas of developmental challenges (water purification, agriculture, drug delivery, etc). Nanomaterial research is a dominant focus with research shifting in areas of promising cutting edge applications namely carbon nanotube and graphene.
- Among the major impediments in research translation are issues of scalability that includes effectiveness of production techniques at commercial scale, process being non-toxic, cost effective, etc. It is promising sign that research in different production methods is visible (as measured through research publications). Risk assessment has become another major area of nanotechnology research activity globally as users demand applications to be non-toxic. Indian research needs urgent attention in this area.
- Indian patenting trends do not commensurate with research trends i.e. number of patents filed by Indian assignees is significantly less. However, it is promising to observe strong connect with patenting happening in areas of developmental concerns. Majority of patents are in nanomaterial application for treatment of cancer, nerve disorders; drug delivery systems, fuel cells, solar cells, sensors for biomedical application and environment impact assessment, water treatment and coatings. Limited involvement of firms from India in research as well as in patenting activity is an area of concern.
- The detailed analysis of 300 firms located in India (either Indian firm or MNC) shows that more than 50% of these firms are actively exploring nanotechnology for enhancing the capability of their established products while around 40% are involved in bulk production of nanomaterials. Location of firms has strong dependence with presence of reputed academic/research institutions where there is active and promising nanotechnology research.
- Nanotechnology applications visible in Indian market are from public as well as private sector. Few public funded organisations are visible in research translation. Some of them are IIT's, CSIR, University of Delhi, IACS and ARCI. The technologies developed are in different domains like energy storage, production and conversion, water treatment and remediation; disease diagnosis and screening, drug delivery systems and textiles.
- Regulation and standard activity requires urgent attention. Broadly when we examine EHS/ELSI issues, we find that the response from India is inadequate. Dedicated programme within the umbrella nanotechnology programme needs to be devoted for EHS/ELSI, standard adoption and development. Framework for regulation needs to be developed by actively involving different stakeholders. India needs to actively participate in international standardisation activities like ISO, IEC and IEEE. Interventions and opportunities need to be created for taking strategic positions in these institutions.

Strengths	Weaknesses
• Research competency is visible in different domains. India emerging as the 4th most prolific producer of research papers in this area, makes a strong assertion of its research capability. • Institution INUP & CoEs developed by government for promotion of nanotechnology research have emerged as a useful model for building competency. • Star scientist with dedicated research groups • Research activity spread across multi-centre • Public push high with nanotechnology being seen as enabler for strengthening innovation across different sectors. • Patents visible in different areas particularly in areas of developmental challenges. • Products developing in different areas. • Involvement in new production methods	• Indian nanotechnology programme is primarily a publicly driven initiative with weak industry participation. • Research not linked to downstream end of the value chain. Patenting activity restricted mainly to public institutions. Expertise needs to be developed for patent examination in this field. • Lacking institutional mechanism for scalability of R&D, Risk assessment. • Dedicated support not visible for indigenous instrument creation. • Issues of EHS/ELSI do not find adequate funding support. Standard creation and adoption shows limited support. • Only initial intervention towards developing regulatory framework. No clarity whether approach would be to create sector specific regulation, or strengthening existing sectoral regulation to incorporate nanotechnology concerns or creating umbrella nanotechnology regulation framework. • Foresight exercise to strengthen existing programs or develop new roadmaps not visible. • Need for creating more awareness of nanotechnology facilities existing in the country.
Threats	Opportunities
• Advanced OECD countries over the years have developed institutional structures and mechanisms for successful commercialisation of new technology based products. This provides them wherewithal for entering an emerging area like nanotechnology then for countries like India where institutional mechanisms are developing. • Shrinking white spaces as nanotechnology patent thickets are emerging in different application domains. Patent entanglement may impede translation. • Regulatory issues may impede nanotechnology innovation and commercialisation. Emerging countries like India would find it more difficult to negotiate this situation. • EHS/ELSI issues may impede exploitation of research.	• Opportunity to address bottom of pyramid solutions. Efforts have been undertaken in some areas of developmental challenges (for e.g. water, drug delivery). • White spaces exist in areas of developmental challenge. • Nanotechnology intervention can provide significant value addition to Indian products and processes. • Unmet challenges can be addressed through nanotechnology intervention

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For suggestions/feedbacks, please contact: sujit@nistads.res.in

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