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REVIEW

Status of Nano Science and Technology in India

Shilpanjali Deshpande Sarma · Manish Anand

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Abstract Perceived globally as an enabling technology with multiple applications and revolutionary impact, nanoscience and technology has been keenly embraced by developing countries like India for socio-economic and industrial benefits. Several advances have been made by India in this emerging technology since the turn of the century. The present paper examines the Indian engagement with nanotechnology across the policy, academic, industry and sectoral domains. The study reveals that the nanotechnology endeavour in India has been shaped by the state, primarily led by DST and public funded R&D institutions although it has witnessed expanded participation via the involvement of other actors both in the public and private domains. The other funding agencies such as DBT and DIT, private research institutes, large firms, industry associations, civil society organizations and individual states are emerging as key players in directing India's nanotechnology trajectory. After establishing this context, the study assesses the role of the main players in sculpting the nanotechnology's course in India. A formal nanotechnology initiative, the NSTI in 2001 was the culmination of previous fragmented beginnings in nanomaterial sciences. The study reviews and examines the goals and initiatives under the DST led flagship programs alongside those assumed by other players through the lens of the capacities that are being created to expand nanotechnology R&D in India. The support for R&D projects, institutional, infrastructure and human resource developments as well as forging collaborations are the key dimensions of government role in the national nanotechnology domain. Industry role on the other hand has been to give shape to technology development and concrete applications in various sectors in individual capacities or even through collaborations with public institutions as emphasised in the NSTM. In addition, the paper also analyses the research avenues in nanotechnology being undertaken in India and shows that alongside fundamental research in nanomaterial synthesis and characterization, applied research and application development in the health, energy, water, agriculture, environment, electronics and textiles are also being assumed. Identifying nanomedicine as a prominent sphere of research in India it gives a detailed account of the actors, research and technologies being developed in this sphere in both public and private domains. Finally the study highlights the outcome of nanotechnology in the research domain by the way of growth in publications and patent numbers. Despite limited resources as compared to developed nations, India has developed a strong foundation for nanotechnology research. We can easily meet the societal and economic needs by strengthening our innovation capabilities.

Keywords Nanotechnology · India · Policy · Actors · R&D trends · Nanomedicine

Introduction

The domain of nanoscience and technology broadly constitutes the manipulation of materials that are below 100 nm in size (in at least 1 dimension), which possess unique physico-chemical characteristics and also involves the development of nano-devices as well as applications that incorporate these materials in order to harness these properties displayed at the nano-scale. This field is widely perceived as the next technology revolution due to the transformations it can enable in crucial sectors such as chemical engineering, information,

S. Deshpande Sarma (✉) · M. Anand
Science, Technology & Innovation Area, The Energy and Resources Institute (TERI), New Delhi, India
e-mail: shilpas@teri.res.in

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communications, electronics, pharmaceuticals, renewable energy, defence equipment and many others. By the year 2015 it is forecasted that nanotechnologies will generate business worth US $ 1 trillion in global markets [1]. Aside from the economic benefits that nanotechnology can bestow, scientific endeavours in this field are anticipated to contribute to significant societal gains especially in the spheres such as health, agriculture, water treatment, energy production and storage [2]. Consequently, the promise of the socio-economic benefits that can be derived from nanotechnology has resulted in both developed and developing country investment and R&D engagement with nanoscience and technology. Although nanotechnology is perceived as a resource intensive technology, developing countries like India, China, Brazil, Sri Lanka have initiated comprehensive programs in this domain despite resource constraints. The articulation by the US of its national nanotechnology policy in 2001 was instrumental in providing developing countries with an impetus to chart out potential strategies in this field. It is widely perceived by governments and policymakers in these countries that early engagement with nanoscience and technology could facilitate a window of opportunity for developing countries to "leapfrog" in terms of scientific progress to not only catch up with their developed country counterparts in terms of R&D but also develop core areas of expertise to enhance industrial competitiveness. Nevertheless, while this has ensured key efforts by state agencies in terms of funding research and developing research capacities and a general flurry of developments in the policy arena, industry participation in developing country contexts has been characterised by a few players and comparatively less investments than in the public sector. Long gestation of R&D, risk of technology failure and uncertain markets may have prevented the early participation of industry in the trajectory of nanotechnology in developing countries although the role of industry is still emerging and a few applications have entered the market.

India's formal and visible engagement with nanoscience and technology was initiated in the year 2001 with the commencement of the Nano Science and Technology Initiative (NSTI). This program is credited as being instrumental in propelling several developments in the nanotechnology R&D landscape in India. However, India's engagement with the nanosciences, especially in the area of material science commenced during 1980's and achieved significant momentum in the late 1990s resulting in the NSTI. Using the achievements under the NSTI as a foundation, the nation embarked on a mission mode program, in 2007, namely Nano Science and Technology Mission (NSTM) which is to continue until 2012 and has been granted funds to the tune of INR 1000 crore (approximately US$ 254 million) [3]. Aside from promoting research in the area of nanoscience and technology these umbrella programs were initiated as avenues to facilitate capacity building measures and strengthen the nation's ability to undertake hi-tech R&D in this field. The Department of Science and Technology (DST), the nodal agency for coordinating S&T endeavours under the Ministry of Science and Technology has been at the helm of both the NSTI and NSTM. Aside from DST, other state funding agencies such as Department of Biotechnology (DBT) and Council for Scientific and Industrial Research (CSIR) both also under Ministry of Science and Technology as well as others like Ministry of Communications and Information Technology, Ministry of Health and Family Welfare are also involved in funding nanotechnology research. On the other hand several public sector R&D institutions, over 30 in number have assumed R&D in the area of nanoscience and technology, the foremost being the Centres of Excellence (CoE) established under the NSTI. Embarking on both basic and applied research, some of the key areas these institutes have focused on are examining routes of synthesis for various nanomaterials and investigating their properties, developing nanoelectronics, devices and biosensors, studying drug delivery mechanisms. In fact research at the intersection of nanotechnology and life sciences, especially nano-biotechnology is one of the leading areas of research in the country. Altogether India's nanotechnology initiative is largely a public driven initiative with industry participation in its nascent stage. Yet established companies such as Reliance and Mahindra & Mahindra as well as SMEs like Velbionanotech have invested in this area and are engaged in product and research development.

India has witnessed a tremendous progress in the area of nanoscience and technology over the last decade in both the policy making and R&D sphere. This is especially indicated by the number of publications and patents that it holds in the international arena as well as the few applications such as the nano-scale silver based water candle filters that are beginning to emerge in the market place. Several initiatives and developments have been instrumental in bringing India to the position of strength it has in nanotechnology R&D in developing countries and is beginning to acquire at global platforms.

In the above context, this paper seeks to review the progress in nanoscience and technology in India both in the policy and R&D arena in order to understand how this capacity for nanotechnology R&D was created. The key players both in the public and private domain are examined along with a brief description of the initiatives that have been undertaken to promote this technology in the country. The major institutes, both R&D institutes as well as universities engaged in nanoscience and technology research are described followed by an account of the key areas of R&D in the nano domain. Given India's strength in the field of biotechnology and pharmaceuticals, R&D at the junctions of nanoscience, life sciences and biotechnology

merge has been a key area of interest for scientists and policy makers in the country. Therefore, a comprehensive account of the nanoscience and technology research undertaken in the health as well as toxicology domains is undertaken for an understanding of the direction of this research in the country. Overall the present research aims at providing an insight into the events and key factors that have been involved in shaping India's nanoscience and technology trajectory and facilitating its rise in this cutting edge domain.

Nanoscience and Nanotechnology: a Primer

The term nanoscience is usually used to denote research that deals with understanding phenomenon at the nanoscale, the control and manipulation of nanomaterials as well as the investigation of their properties [4]. Nanomaterials are substances that are between 1–100 nm in size in one, two or three dimensions and possess unique physicochemical characteristics not observed in their bulk counterparts. Of several types, nanomaterials are of great interest as their unusual properties could enable novel applications or help enhance existing products and processes. On the other hand 'nanotechnology' refers to the synthesis, analysis, manufacture and application of materials, products and systems that are at the nanometer scale using various tools and methods [4]. Generally, the term nanotechnology is used as a reference for both nanoscience and nanotechnology domains, however in scientific parlance, nanoscience is customarily used to indicate investigations that represent fundamental and other research that for instance examines the synthesis and characterisation of nanomaterials, facilitates insights into their unique properties, allows their manipulation and also research that thereby identifies their use in potential applications. In contrast, nanotechnology signifies the development of specific products or applications that comprise of nanomaterials. It could also refer to devices and systems that are themselves at the nanoscale such as sensors etc. Nanosciences and technologies draw from several disciplines ranging from chemical and material sciences, physics, engineering and biological sciences. Nanotechnology is multidisciplinary, even interdisciplinary and can lend itself to other technologies to facilitate enhanced materials and applications. In fact, in many cases the term 'nanotechnologies' is used in place of its singular counterpart, as in effect the field denotes numerous technology prospects in a variety of sectors rather than a single kind of technology intervention.

The convergence of nanotechnology with biotechnologies and information technologies has driven vast speculation on the advantages and benefits they could bestow on society. Nanotechnologies are being hailed as transformative and enabling in nature especially due to their ability to contribute to diverse sectors and facilitate socio-economic gains. These prospects have elicited keen interest in developing nations like India for the development of R&D in this domain and have also prompted significant responses in these nations in terms of investments and policy initiatives.

Architecture of the Nanotechnology Domain in India: Key Players

The emergence of nanotechnology in India since the turn of the century and until the present has seen the involvement of a diverse set of actors (Fig. 1). Broadly these include government agencies that fund and promote research in the area of nanoscience and technology, publicly funded research institutes and universities that undertake R&D in this area as well as the participation of private academic or research institutes. Other important players in the Indian scenario include industry associated with R&D and product development in this domain as well as industry associations.

In general, actors known to play important roles in technology development worldwide include knowledge transfer set ups (technology incubators or technology parks), venture capitalists that fund research in SMEs and regulatory agencies that prescribe boundaries for R&D and commercialisation. A couple of technology incubators have been established in R&D institutes engaged in nanotechnology in India for assisting product development and the intention of establishing nanotech parks have invariably been made known from various quarters. Nevertheless, the participation of technology transfer and venture capital bodies has been rather insignificant for now as has also been the role of regulatory agencies although policymakers have recently articulated the need for the development of appropriate regulations for nanotechnologies in the country. The role of civil society organisations and media to either promote or oppose the technology amongst the public has also been negligible barring a few examples, although some described as civil society/non-for-profit are aimed at building links between academia and industry (Fig. 1).

State Support: Defining the Nanotechnology Trajectory

Since nanotechnologies can contribute to a variety of sectors and also span several disciplines, a wide variety of state agencies are involved in supporting nanoscience and technology in this area. Under the Ministry of Science and Technology the primary agencies involved with nanotechnology are DST, DBT and CSIR. DST is the nodal department for coordinating activities of nanoscience and technology in India which it does through the Nanoscience

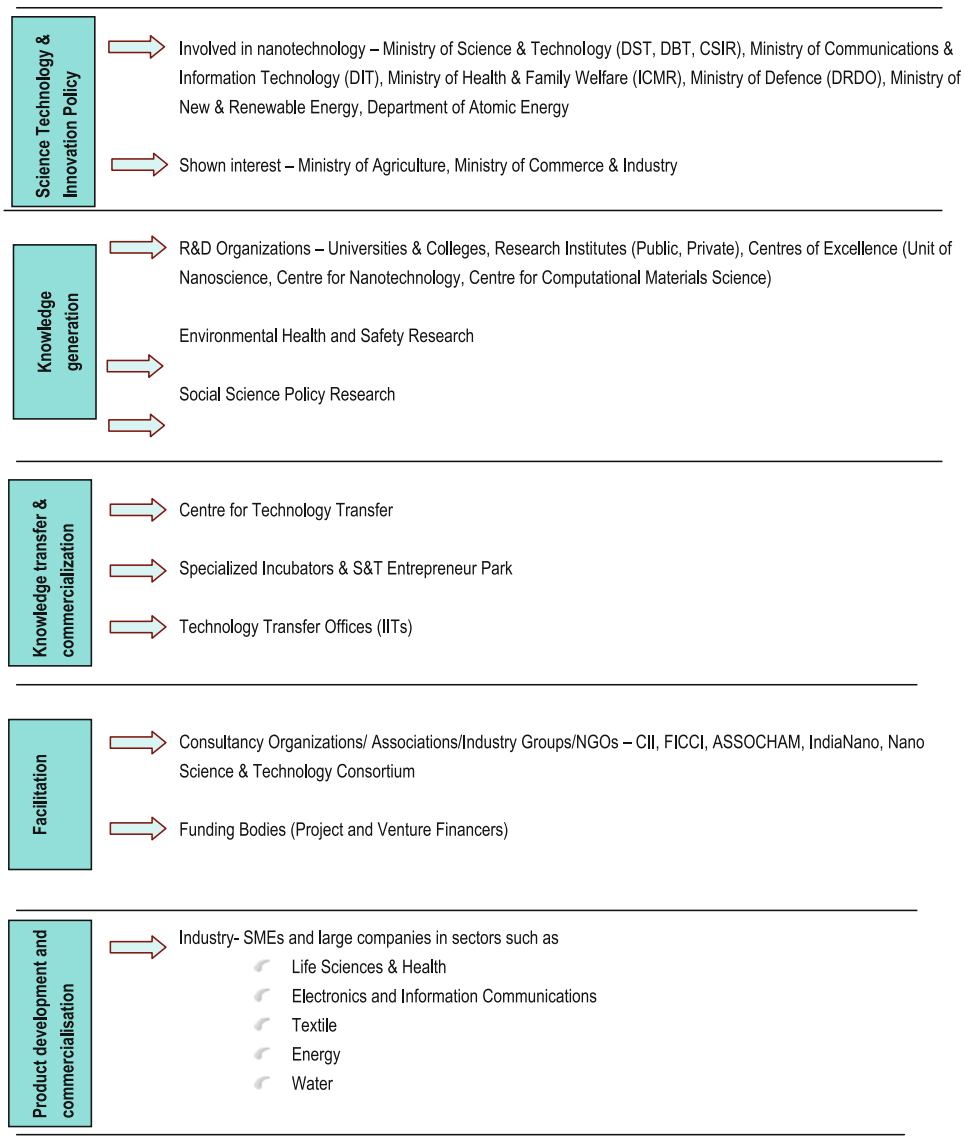

Fig. 1 Mapping of stakeholders in the nanosciences and technology domain in India

and Technology Mission (NSTM). DBT, on the other hand, is primarily involved in promoting the field of biotechnology in India and therefore has been involved in the sphere of nano-biotechnology. CSIR which is constituted by a network of 38 laboratories that undertakes research in areas of scientific and industrial importance also supports R&D in the area of nanoscience and technology in its laboratories. Other agencies supporting nanotechnology in India include the Department of Information Technology (DIT) through the Ministry of Communication and Information Technology in the area of ICT and electronics, Indian Council of Medical Research (ICMR) under the Ministry of Health and Family Welfare for developing applications in the context of health as well as Ministry of New and Renewable Energy (MNRE) that is encouraging nanomaterial research for energy production and storage. Aside from these organisations other agencies such as the Department of Atomic Energy (DAE) and Defence Research and Development Organisation (DRDO), a network of 50 laboratories under the Ministry of Defence have also been sponsoring research in the area of nanoscience and technology.

Overall, DST appears to be most instrumental in developing and shaping India's engagement with nanotechnology followed by the other agencies amongst which CSIR, DBT and DIT are playing prominent roles. While DST, CSIR and to some extent DRDO promote R&D in diverse areas ranging from material science to electronics and health, agencies like DBT, DIT, MNRE are actively contributing to the development of nanotechnology in their chosen areas. Some other ministries such as, the Ministry of Agriculture through Indian Council of Agricultural Research (ICAR) have also displayed considerable interest in developing nanotechnology R&D in the sphere of agriculture. The Ministry of Commerce and Industry has also taken some interest in promoting nanotechnology developments in the country for enabling industry participation.

Public Sector R&D Institutions: Building the Knowledge Base

Research and development in the area of nanoscience and technology is being predominantly undertaken in public funded academic and research institutes making them key players in the Indian domain. While several universities and research institutes across India are now engaged in nanoscience and technology research, DST under the NSTI established 19 Centres of Excellence (CoE) in various institutes. The nineteen CoEs comprise of eleven Units of Nanoscience and seven Centres of Nanotechnology (Fig. 2) as well as a separate Centre for Computational Materials Science. Altogether out of the 19 CoEs, 18 are hosted across thirteen distinct public funded institutions that have established reputations for research and adequate infrastructure, whereas one CoE, a Centre for Nanoscience is based at a private research organisation. The Units were created with the intention of pursuing basic research in the various areas of nanoscience and nanoscale systems whereas the centres have been established for encouraging time bound R&D in niche areas especially directed towards the development of specific applications. The CoEs are established in different kinds of institutes- the highest number hosted by autonomous institutes (11) followed by deemed universities (4), Central/State Universities (2) (Fig. 2). One CoE each is hosted by CSIR lab and as described earlier a private university (Fig. 2). In addition five out of the fourteen institutions (three autonomous institutes and two deemed universities), namely the S.N. Bose National Centre for Basic Sciences (SN Bose NCBS), Indian Association for the Cultivation of Science (IACS), the Indian Institute of Science (IISc), Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) and IIT Kanpur, host a Unit for Nanoscience and Centre for Nanotechnology each, covering over half of the total CoEs. In terms of location, the 14 institutes hosting either Units or Centres or both CoEs, three each are located at Kolkata and Bangalore followed by two in Pune. In addition Chennai, Kochi, Mumbai, Delhi, Kanpur and Varanasi hosts one such institution (Appendix).

Aside from the CoEs, several other institutes particularly the CSIR labs and the other IITs (Guwahati, Kharagpur and others) are also pursuing R&D in these areas. Several laboratories amongst the 38 under CSIR have been extensively involved in research in the field of nanotechnology. More significantly, aside from research and development in the area of nanomaterials and associated applications, CSIR laboratories such as Indian Institute of Toxicology Research (IITR) and Central Drug Research Institute (CDRI) have been associated with studies related to understanding the toxicological impacts of nanoparticles. Other autonomous institutes like the International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) and National Institute of Pharmaceutical Education and Research (NIPER) have also been engaged in extensive research in nanomaterials synthesis, application development and drug delivery, respectively.

There is a wide feeling amongst policy makers and scientists that strengthening the nation's capacity in nanoscience and technology would necessitate the augmentation of institutes capable of undertaking world class R&D in this area. In fact, Dr T. Ramasami, DST secretary has stated that a critical mass of 150 working groups would be required to elevate the quality of nanotechnology R&D in the nation [5]. He also mentioned therefore, that the aim is to develop a conglomeration of about fifty to sixty technology units that include institutes like the IITs and NITs and also to develop nano clusters across the country [6]. This intention has therefore, been translated into the creation of new institutions for nanotechnology in the country as also the funding for nanoscience and technology centres in several existing universities. For example, three Institutes of Nano Science and Technology (INST) at Mohali, Bangalore, and Kolkata [7] were considered and funds for the proposed institute at Mohali have been allocated [8]. It is proposed that these institutes will focus on research related to nanotechnology in the context of agriculture and biotechnologies. The institutes at Mohali and Kolkata are planned in partnership with the proposed Indian Institute of Science and Technology whereas, the one in Bangalore has been planned in partnership with IISc and JNCASR. The CoEs and these proposed INSTs are being developed as specialised centres for nanoscience and technology related R&D [9]. On the other hand, in order to expand the R&D base for nanotechnology in India, investments have been made to create in house centres in various universities. These include for instance two different centres for nanomaterial research created in 2007–2008 at Hyderabad University, Andhra Pradesh and at Madurai Kamraj University, Tamil Nadu. Previously in 2006–2007, another Centre for Protein Nanoscience at Anna University, Tamil Nadu was also created. In 2008–2009, ARCI was sanctioned a grant for the creation of "Centre for Knowledge Management of Nanoscience and Technology" whereas in 2009–2010 funds were granted to the University of Allahabad for the creation of a "Nanophosphor Application Centre" [10].

Overall, as observed from the establishment of the CoEs, the proposed INSTs and funding of centres for nanoscience and technology R&D at other academic and research institutes has been undertaken at diverse locations in India, especially to allow for a decentralised approach to building capacity in India.

Private R&D Institutes: Tiding the New Wave

Several private research institutes have also been involved in nanoscience and technology R&D. Prominent amongst them

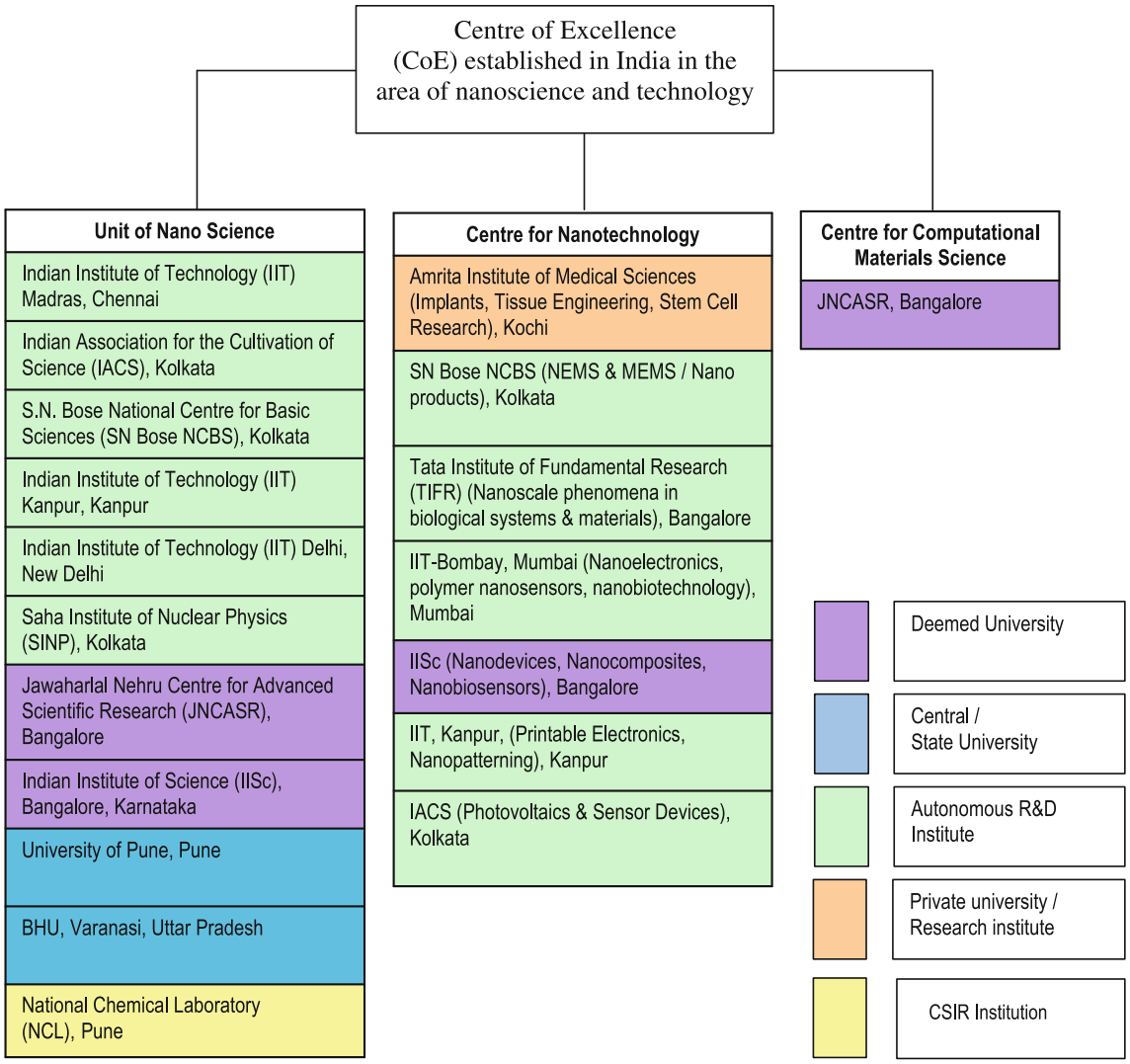

Fig. 2 Centre of Excellence established in India under NSTI. Source of information: The Energy and Resources Institute (TERI). 2009, A review of NT developments as applicable to developing countries

are the Amrita Institute of Medical Sciences which has a faculty devoted to nanosciences and is a designated CoE—A Centre for Nanotechnology. Aside from this other institutes such as Sankara Netralaya, The Energy and Resources Institute (TERI), Birla Institute for Technology and Science, Amity University, SASTRA University are involved in nanoscience and technology R&D. Several of these institutes have displayed a keen focus in the areas of nanomaterial synthesis, nanobiotechnology and the area of nanosciences and health. On the other hand, TERI is also involved in policy related research in the area of nanotechnology.

Industry and Industry Associations: Fostering Collaborations and Innovation

Nanotechnology industry is defined as the group of firms focused on bringing nanotechnology processes, materials, tools and devices into the market [11]. Nanotechnology industry is still at a nascent stage in India. There are a limited number of companies engaged in research and product development on nanotechnology. Around 32 companies have been found to be actively engaged in nanotechnology covering the areas of materials and surface engineering, biotechnology, instruments and equipment and, electronics. However, much of the research and technology development work in India has been undertaken in the area of nanomaterials. The nanotechnology industrial landscape in India is characterized by companies working on nanotechnology at various levels viz., start-ups on nanotechnology and existing companies that have started working on nanotechnology. A handful of start-up companies have emerged in the last 4–5 years. Majority of them are providing consultancy, market research and training, while product development efforts are directed towards chip design and development,

nanomanipulation, nanomedicine and nanomaterials (e.g. carbon nanotubes, silica and alumina). These start-ups are mostly at product development stage with limited commercial success. Lack of seed capital is hampering these product development efforts. Indian venture capital firms, especially after the IT bust at the turn of the century, are risk averse and are reluctant to provide seed funding to unproven businesses. Start-ups like Monad, Innovations Unified Technologies, INNANO Technologies, Nano Bio Chemicals India Pvt. Ltd., NanoFactor Materials Technologies, QTech Nanosystems, Ogene Systems India Pvt. Ltd., Aisin Cosmos R&D Co. Ltd., United Nanotechnologies Pvt. Ltd. NANOSHEL is focusing on nanomaterials and surface engineering. Other start-ups like Velbionanotech focuses on biotechnology and biomedical applications. There are also established companies that had started engaging with nanotechnology both for improving products in their existing businesses and exploring other businesses for the next generation. Companies like Reliance Industries, Mahindra and Mahindra, Tata Chemicals, Ashok Leyland, Asian Paints, Crompton Greaves are working on nanomaterials research and product development. Panacea Biotech, Dabur Research Foundation, Centre for Advanced Research and Development, Bharat Biotech, Lifecare Innovations focuses on the interface between biotechnology and nanotechnology. A few companies like, Veeco Instruments Inc., Forevision Instruments has their focus area as instrumentation and equipment development. Also, some companies are working in the area of nanoelectronics such as, Cranes Software International Ltd., Bharat Electronics Ltd., Samtel Color Ltd. In addition to the above companies, industry associations like the Confederation of Indian Industry (CII), Federation of Indian Chambers of Commerce and Industry (FICCI), Associated Chambers of Commerce and Industry (ASSOCHAM), Society for Indian Automobile Associations (SIAM), Automotive Component Manufacturers Association (ACMA) also play an important role in fostering nanotechnology development as an industry-interface organization and bringing together various stakeholders to explore the potential of nanotechnology.

Not-For-Profit and Civil Society Organisations: Promoting Inclusiveness

A few not-for-profit organisations are associated with nanotechnology developments in India, however their role is mostly in the capacity of linking academia with industry. For instance, The Nanotechnology Research and Innovation Foundation is a non-profit organization supported by academic and industry experts such as National Chemical Laboratory, Girvan Institute of Technology and The Centre for Materials for Electronics Technology and is funded by IndiaCo, a private equity investment holding company that invests in hi-tech companies. Its aim is to provide a platform to stakeholders for R&D collaboration in advanced technologies including nanotechnology. In January 2006 a strategic partnership between the Nanotechnology Research and Innovation Foundation and the Regional Research Laboratory, Trivandrum (RRL-T) was forged to leverage their combined expertise to respective expertise facilitate the commercialization of RRL technologies with industries in India and across the globe. The Nano Science and Technology Consortium [12], another non-governmental, industry-managed and promoted organization seeks to create a platform conducive for the growth, promotion and collaboration between industries, academics and government in the nano domain through consultative, advisory and educative processes.

On the other hand, The Energy and Resources Institute, a not-for profit research institute, through its research on policy issues in the domain of nanotechnology and developing country capabilities has been facilitating information dissemination and interaction amongst the various stakeholders on key dimensions of this technology. The various stakeholder dialogues organised by the institute has been a platform to discuss aspects of R&D innovation and capacity building, benefits, risks, regulatory and socio-ethical issues in the context of nanotechnology and its implications for developing countries. Moreover, these platforms have successfully brought together scientists, social scientists, technology developers, policy makers, lawyers, NGOs, media to discuss and debate the aforementioned issues. Through these stakeholder engagement and dissemination initiatives the institute has donned the role of a civil society organization that seeks to contribute to the sustainable development of nanotechnology in India.

Policy Support for Nanotechnology in India: Role of State Agencies

Key Programs and Investments

Mapping the beginnings: Although R&D in nanoscience and nanotechnology has received a great impetus since the turn of the century, research in the area of nanomaterials is not new to India. Although not formally being described as nanosciences research, R&D in the spheres of material sciences and chemistry that was associated with the nano domain was prevalent in the country since the 1980's. For instance the program on the 'Intensification of High Priority Areas' launched during the 6th Five Year Plan and which is said to have enormous impact on scientific R&D in India included support for research on nanomaterials [13]. Later in 1997 a DST created committee sought to look into the prospects for nanotechnology in India and also provide research funding. During this period a

program on Nanocrystalline materials that funded projects focused on synthesis and properties of nanomaterials was initiated by SERC placed under DST [14]. Altogether, the late 1990's were characterised by smaller nanoscience related programs as well as other general grant programs that supported research in this area. In the year 2000, a 5 year program on smart materials (the National Program on Smart Materials) that focused on aerospace and biomedical sciences was conceptualised and launched jointly by five government agencies- DRDO, DOS, CSIR, DST and MIT. This program that had been granted around US$ 15 million and which also supported nanomaterial research amongst other areas is considered instrumental for future independent initiatives in the spheres of micro and nanotechnology [15]. The aim of this initiative was also to support development of applications, processes and technologies in the sphere of nanotechnology and special emphasis was laid on issues of national importance such as access to clean water, alternative energy sources etc.

At the beginning of this decade, an expert group on Nanomaterials: Science and devices was conceived by DST to comment on the existing expertise in the nanotechnology domain in India and the direction for the future. The committee highlighted several significant points, amongst them were that while a good research base especially in physics and chemistry exists for nanomaterial research, there was a need to encourage greater basic as well as goal oriented applied research within the country together with enhancing infrastructural 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 [16]. Together all of these smaller initiatives undertaken prior to 2000–2001 culminated in the creation of the first comprehensive program in the domain of nanotechnology in India, the Nano Science and Technology Initiative (NSTI).

Nano Science and Technology Initiative (NSTI): Laying the foundation: The government's decision to prioritise research in nanoscience and technology in the 10th Five Year Plan alongside developing a clear framework for building capacity in this domain helped evolve the NSTI. After the strategy paper delivered by a National Expert Committee, constituted by DST supported the creation of such a framework, a panel on nanotechnology was established under Prof C.N.R. Rao widely proclaimed as the father of Indian nanotechnology. These efforts helped conceive the NSTI which was funded at INR 100 crore (approximately US $ 15–20 million) and undertook broadly the following objectives-

- Support R&D projects in nanoscience and technology.
- Establish Centers of Excellence and strengthen characterization facilities
- Develop human resources
- Instigate and encourage international collaborative programs
- Initiate joint Institution Industry Linked projects and Public Private Partnership activities [10]

The thrust areas of the NSTI are described in (Fig. 3).

Overall, the commencement of NSTI brought about a new era of progress in India in the realm of nanotechnology related R&D. This period was characterized by several developments across India in the realm of nanoscience and technology all of which were enhanced by the encouragement and pro nanotechnology stance by Dr A.P.J. Abdul Kalam, the then President of India. The initiative also facilitated the strengthening of research in new and existing areas, the creation of the Units of Nanoscience and Centres for Nanotechnology as CoE and augmentation of infrastructure. In addition it helped propel several international collaborations with the Indian scientific establishment and also made attempts at initiating the much needed linkages between academia and industry. In short, as intentioned by policy makers it helped establish a reasonable foundation of nanoscience and technology research in the country.

Nano Science and Technology Mission: Increasing the momentum: Areas of research priority in India have traditionally been undertaken in a 'mission mode' capacity. Therefore, during the NSTI reign, and especially encouraged by a good response of the scientific committee to this program, the need for mission mode initiative in the realm of nanotechnology was felt by policy makers, in order to propel the nation towards a strengthened position in this domain. As a result, the government in 2006–2007 approved the launch of the Nanoscience and Technology Mission with DST at its helm, a budget of Rs. 1,000 crore (approximately US$ 254 million) for a 5-year duration (2007–2012) [3]. The ten-fold increase in the NSTM's budget from that of the NSTI has been sanctioned primarily with the aim to leverage the progress made during the last program to capitulate India to a position of strength in the nanotechnology arena. The Mission Council chaired by Prof C.N.R. Rao guides the NSTM and under which two committees, the Nanoscience Advisory Group and the Nano Applications and Technology Advisory group have been created to guide basic science research as well as R&D for technology applications. The focus areas of the NSTM are to -

- Further intensify and consolidate basic research in this domain
- Promote and support goal oriented R&D for developing applications
- Create greater number of infrastructural facilities
- Strengthen human resources
- Enhance collaborations [10].

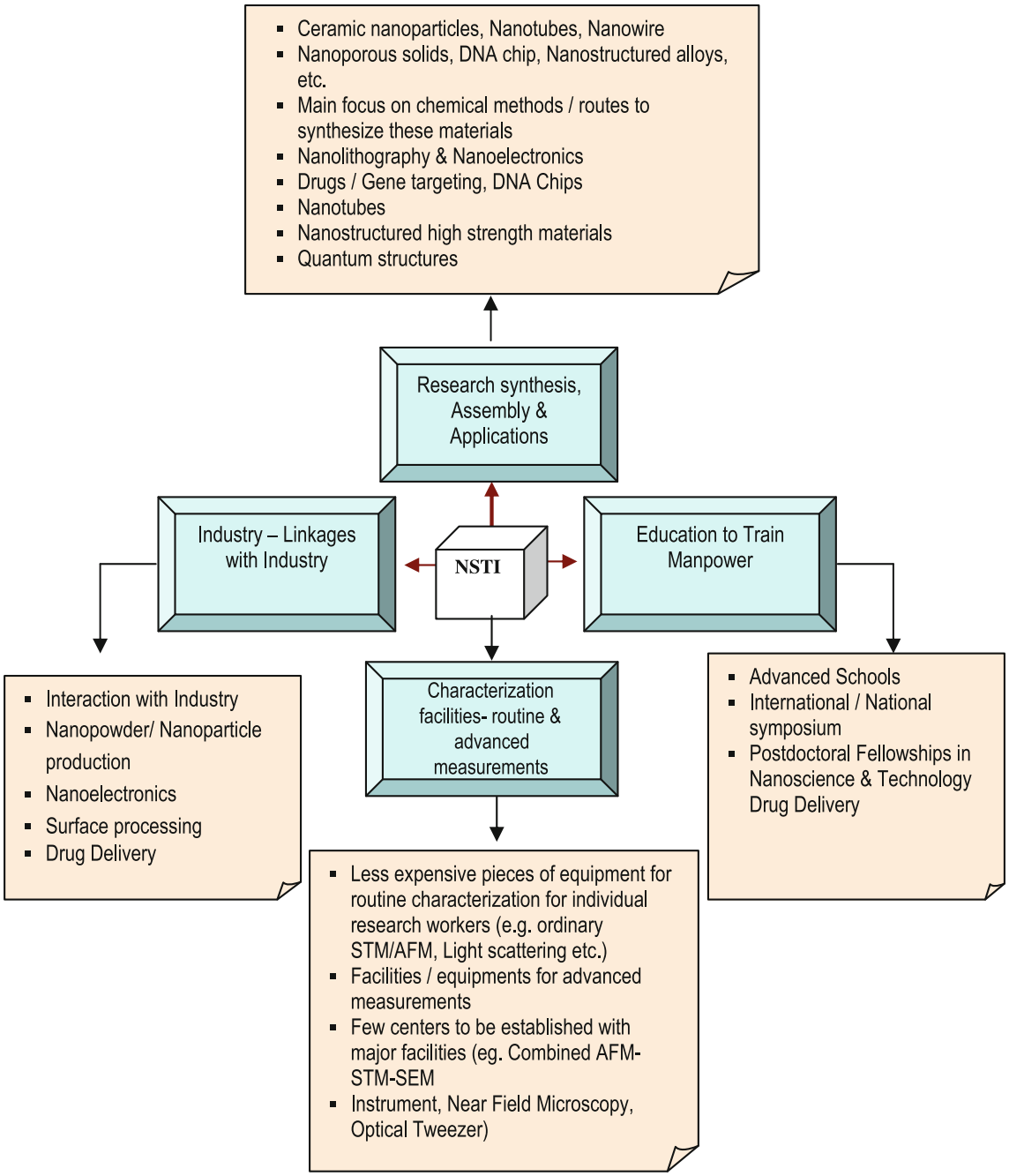

Fig. 3 Thrust of the Nanoscience and Technology Initiative (NSTI). Source of information: http://nanomission.gov.in, adapted from The Energy and Resources Institute (TERI). 2009, A review of NT developments as applicable to developing countries

From 2006 onwards, several activities have commenced in this sphere and copious funds have been allocated for developing capacity in these areas. Activities that were foreseen and undertaken in the focus areas are described in Fig. 4. At the present time, NSTM is perceived as the key driver for several of the developments and activities being undertaken in India in the realm of nanoscience and technology.

Aside from DST, DIT also appears to have initiated a 'Nanotechnology Development Program' in 2004 under its Nanotechnology Initiative Division created to develop R&D in the area of nanoelectronics and nanometerology. The focus of this program has been on developing infrastructure within institutes in these areas and supporting projects in these areas. DIT is known to have spent approximately between INR 25–40 crores each year between the years 2004–2007 on this program [17]. In contrast the other agencies such as DBT, CSIR, DRDO, DAE, ICMR and MNRE, while not creating special programs have been supporting and providing financial

assistance for nanoscience and technology R&D through other mechanisms. Although exact figures are unclear, funds allocated by DBT and CSIR are known to be large.

Overall, the initiation of large programs and augmented support to nanoscience and technology has been fuelled by the desire of the government and scientific community to create capabilities on par with developed nations in the domain of nanotechnology, who have been observed to invest copious amounts in R&D in this area. There is also a feeling amongst the Indian scientific establishment that the lost opportunity in the sphere of semiconductor manufacturing which, resulted from limited funding and lack of backing for scientific endeavours in this area, must not be repeated with nanoscience and nanotechnology. Therefore, scientists and experts in general have emphasized that early investments in nanotechnology are crucial as it would translate into an environment for cutting edge science, publications, technological innovation and products as well as IPR which is much needed in this knowledge driven globalized world. On the other hand, the increased investments in nanoscience and technology are also in part a result of an overall enhancement in S&T budget of India. Specifically a 21 % increase in the national S&T budget was observed in 2007–2008 from the previous year [18]. It is therefore interesting to note that in the budget outlay for DST in the 11th Five Year Plan funds allocated for the NSTM was the third highest amongst that allocated for all schemes (existing and new) whereas amongst the existing schemes its funding was second only to that of Drugs and Pharmaceutical Research. Nevertheless, nanoscience and technology being resource intensive, in terms of materials and infrastructure need to support R&D, would necessitate large investments for undertaking cutting edge research and translation of this basic research into tangible applications and products. This is why the government has advocated the need for R&D driven by public private partnerships and investments by industry in research of mutual interest.

Building Capacity

Enhancing the capabilities of the nation for undertaking cutting edge R&D in the nanosciences and technology and for creating an environment for India to excel in this domain has been the primary aim of government agencies like DST, DBT, CSIR, DRDO, DIT, MNRE etc. Aside

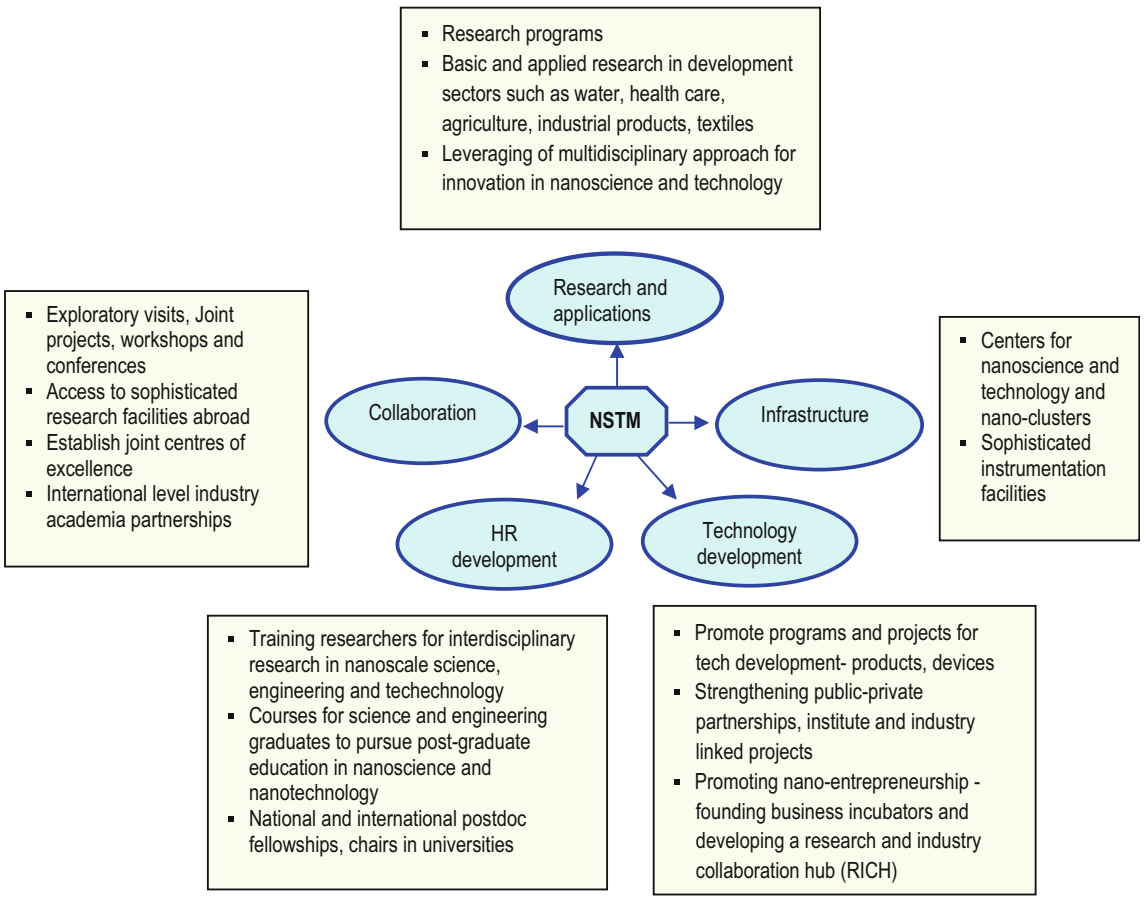

Fig. 4 Thrust of National Nanoscience and Technology Mission (NSTM). Source of information: http://nanomission.gov.in; adapted from The Energy and Resources Institute (TERI). 2009, A review of NT developments as applicable to developing countries, TERI Report

from these central agencies, the expansion of nanotechnology in India has also led to participation of State governments in development of policies to promote nanotechnology. This intention is being facilitated through various avenues such as,

- Allocation of funds for R&D projects in nanoscience and technology and support for fundamental and application oriented research
- Establishing dedicated facilities and centres for R&D in this area and strengthening infrastructure
- Developing initiatives for creation of skilled human resources
- Forging international collaborations

One of the key roles played by state agencies has been provision of grants for research to be conducted in the area of nanoscience and technology. DST through the NSTI and NSTM has funded over 230 projects in this sphere until March 2010 (Fig. 5) [10]. DST is the nodal department for science and technology in India and its mandate covers a variety of spheres therefore the aim has been to develop a broad base for nanoscience and technology research by allocating funds for research in diverse research areas. These areas span basic research especially in areas of nanomaterial synthesis, characterisation and understanding of properties as well as applied research and application development in areas like electronics, therapeutics, renewable energy and textiles etc. However while most of the funding during the NSTI was for fundamental research in nanosciences, there has been an increasing emphasis on product development in the NSTM. Aside from grants available from NSTI and NSTM, the Science and Engineering Research Council (SERC) also under DST has funded nanosciences and technology research under it basic sciences, engineering sciences and fast track programs [19].

DBT has also issued several calls for proposals in the area of application of nanotechnology in fields of biological sciences such as cell biology, biotechnology, medicine, agriculture and food packaging, energy as well as environment (Fig. 6). Several institutes have also been granted project funds for undertaking research in these areas and 42 projects were sanctioned in the year 2007–2008 in areas such as drug delivery, therapeutics, water purification etc. [20]. While DIT has funded over 18 projects in the areas of nanoelectronics and nanometereology [21], MNRE has supported the similar projects in the areas of solar energy and hydrogen storage [22]. Nanoscience research in the areas of chemical and material sciences and engineering sciences are the focus areas of CSIR [23], DAE [24] and DRDO [25] which have provided funds to their constituent laboratories for R&D in these areas. In addition, CSIR and DRDO have also funded projects in the area of nanotechnology and health. CSIR in particular has been instrumental in developing the field of nanosciences and technology. Several of its constituent laboratories have been sanctioned grants for pursuing R&D in this domain although as of now there does not appear to be a formal program on nanotechnology. In several cases research in the nano-sphere in these laboratories is an extension of the research that was being pursued in the areas of other sciences within the laboratories that is tailored towards boosting scientific and industrial R&D that maximizes economic, social and environmental benefits for India. While amongst the CSIR laboratories, NCL is already a designated CoE, other labs namely IICT, CLRI, NML, CDRI, NEIST, IITR and NPL have been working in the areas ranging from nanomaterial synthesis for various industrial applications, drug delivery as well as toxicology [23]. ICMR on the other hand funds institutes both under its purview as well as dedicated funds for extramural research which it has sanctioned for research in the realm of nano-medicine [26].

Public–private partnerships have been a key area of focus for the agencies involved in developing nanotechnology R&D in India, especially in order to create an environment that harnesses lab-scale research to deliver applications and products. It is also a key area of concern as the R&D establishment has traditionally not witnessed over the years as many number of successful academia-industry partnerships as desired due to several challenges. However, fostering such initiatives has been recognised as key for the progress of nanotechnology in the country and therefore the state agencies have been involved in enabling mechanisms to facilitate joint projects between public research institutions and the industry. Foremost amongst them has been DST through which the NSTM has sought to create 'Nano Applications and Technology Development Centres', 'Nanotechnology Business Incubators' as well as 'Research and Industry Collaboration Hubs' [10].

Furthermore, six institution-industry projects worth 40 crores have been facilitated through the nanotechnology

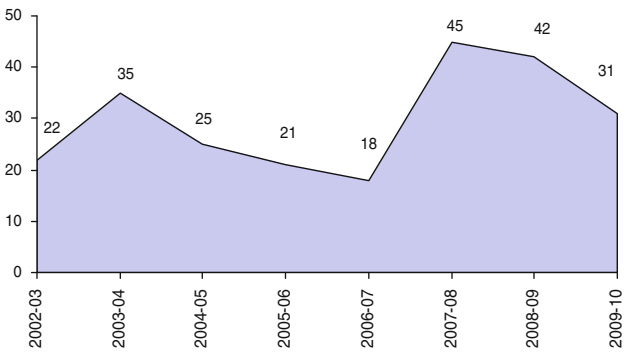

Fig. 5 Distribution of projects funded by DST across years 2002–2010. Source of information: http://nanomission.gov.in and http://dst.gov.in/scientific-programme/ser-serc.htm; TERI, 2010, Nanotechnology development in India: building capability and governing the technology, TERI Briefing Paper

programs with some part of the investments being contributed by industry (Fig. 7) [10]. CSIR's scheme on New Millennium Indian Technology Leadership Initiative (NMITLI) which seeks to develop efficient public–private partnerships through particular identification of key areas for undertaking of research by experts followed by interaction of core groups and regular monitoring of R&D has also been extended to projects in the area of nanotechnology [23].

Development of adequate and suitable infrastructure is essential for the assuming cutting edge research in nanoscience and technology. This necessitates creation of facilities dedicated to nanotechnology R&D as well as the availability of expensive and sophisticated instrumentation, a challenging task in a country that is often perceived as possessing inadequate research infrastructure. However, state agencies are undertaking several measures to prevent the slackening of R&D in nanotechnology due to the lack of state of the art infrastructure. Establishing centres dedicated to undertaking research in the area of nanosciences and technology has been taken up primarily by DST through the NSTI and NSTM. As described in the previous section, these centres include the 19 CoE in public funded academic and research institutes as well as one private institute. New institutions entirely dedicated to R&D in the nano-domain have been envisaged with one in Mohali being funded. Aside from this, several other universities and research institutes have been granted funds to upgrade their infrastructure as well as start facilities especially dedicated to R&D in nanoscience and technology. Table 1 describes the analytical facilities that have been supported by DST at various institutes. While Sophisticated Analytical Instrumentation Facilities have been established in India, a chain of facilities with high end instrumentation such as Atomic Force Microscopy, Scanning Tunneling Microscopy, Transmission Electron Microscopy, Optical tweezer has also been envisaged [10]. DIT has also supported the establishment of a joint nano-electronics centre at IISc Bangalore and IIT Mumbai for which approximately 99.8 crore was invested for 5 years. In another key step, an Indian Nanoelectronics User Program has been created to enable researchers from institutes other than IISc and IIT Mumbai to avail the infrastructure that exists for nanoelectronics R&D. Another facility supported by DIT, the Generic Development of Nanometrology for Nanotechnology at NPL will focus on creating infrastructure for calibration and other techniques [27]. The creation of an institute namely the National Institute of Nanotechnology in Agriculture (NINA), dedicated to research undertaken in nanosciences and agriculture has also been called by the Planning Commission [28].

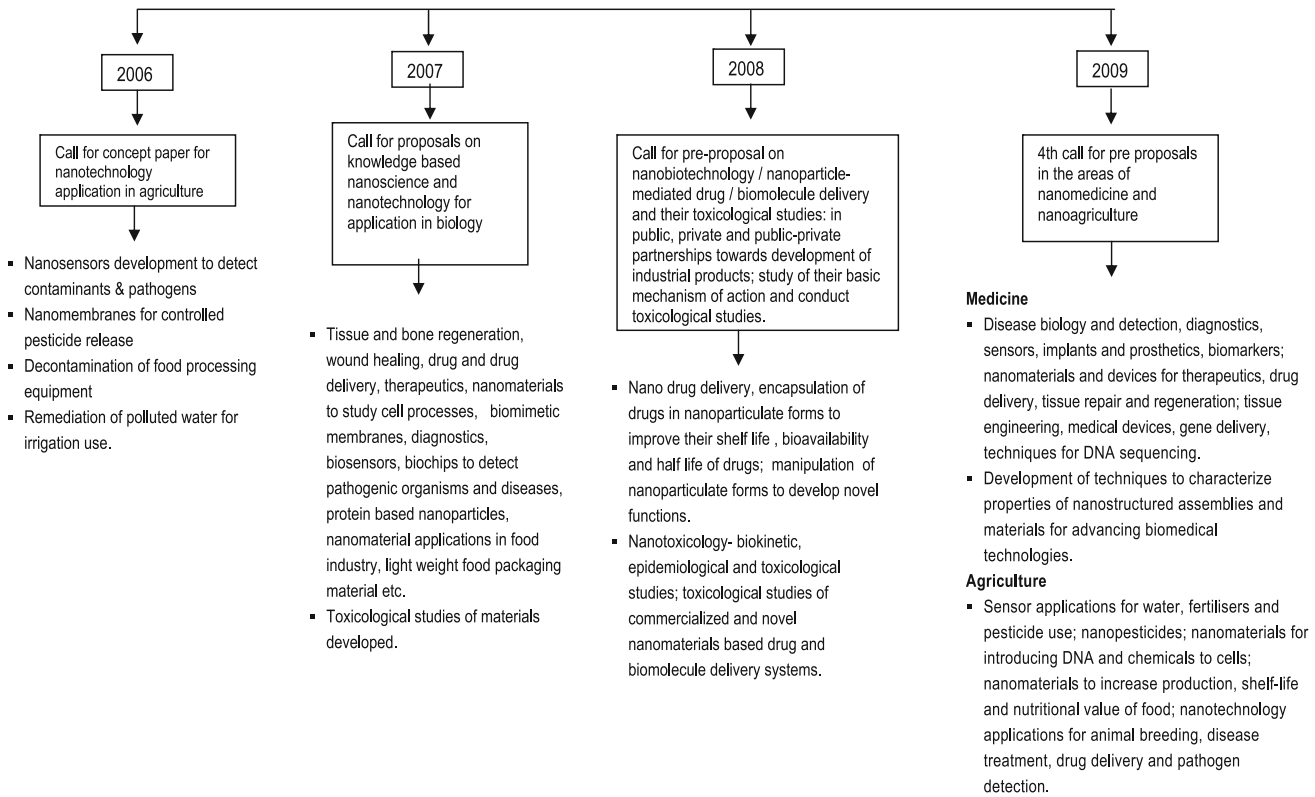

Fig. 6 Calls for proposals on nanotechnology by DBT. Source of information: Compiled from various sources, adapted from The Energy and Resources Institute (TERI). 2009, A review of NT developments as applicable to developing countries, TERI Report

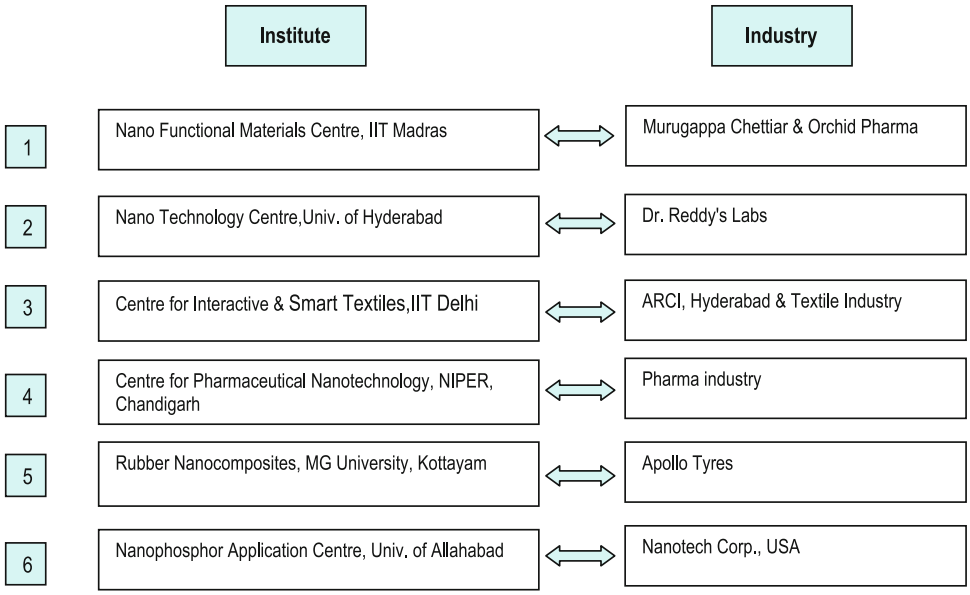

Fig. 7 List of Joint Institute-Industry Projects under the NSTM. Source of information: http://nanomission.gov.in/

In addition to infrastructure development policy makers have also been prioritising the creation of an adequate skilled workforce for undertaking research in nanoscience and technology. Since progress in cutting edge research, increase in publications, patents and product development is directly associated with the existence of qualified and able workforce, several measures are being undertaken in this area to leverage the advantages of a large population of scientific literate and young workforce to create skilled labour in the nanotechnology domain. With the DST secretary Dr Ramasami emphasizing the need to find approaches to "expand capacity to churn out human resources required for development and growth of the nanosector" [29], DST has been leading initiatives to equip the workforce with adequate skills in efforts to harness India's low cost advantage to make India a global destination for nanoresearch much like has been witnessed in the IT sector. Since multidisciplinary and interdisciplinary approaches to research have been identified as key pre-requisites for R&D in nanotechnology, DST through the NSTM has encouraged universities and research institutes with adequate infrastructure to develop postgraduate courses so that students may be trained in the diverse disciplines that constitute nanosciences and technology [10]. The agency has promised of sufficient financial assistance for a 5 year period to institutes for such courses, and JNTU, Hyderabad was the most recent institute to be supported for its M.Tech course. Around fifteen such institutes have been supported for postgraduate courses [8] and some of these have been described in Table 2.

Some other activities in this sphere include funding and organising training programs and Advanced Schools for scientists in specialised spheres. Some schemes such as The Foundation Training Program and Advanced Techno-Management Program for Scientists and Technologists also cover nanotechnology. Other initiatives such as provision of awards and fellowships and support for attending conferences that helps build international networks and enables scientists to train at other international institutes have also been emphasized. Support for organising international conferences attended by industry and scientists from international and established groups have also been granted on occasion. The ICONSAT conference held in 2010 which awards the National Research Award for Nanoscience and Technology is one such premier conference that also encourages student participation [10].

A compilation of initiatives undertaken in the sphere of human resource development are described in Table 3. Through these initiatives the government seeks to create a pool of skilled personnel ranging from postgraduates and doctoral students to scientists in the area of nanotechnology which is vital for the progress of R&D in the country.

The NSTI and NSTM have also been instrumental in forging international collaborations, especially bilateral initiatives with several countries in the area of nanoscience and nanotechnology as a part of S&T agreements. Joint R&D projects and initiatives with countries like the US, Russia, member states of EU and south east Asian countries like Japan, Taiwan etc. have been facilitated as to have scientists visits, joint workshops and conferences. CSIR's International Science and Technology Directorate (ISAD) has facilitated collaborative projects and workshops with several countries such as South Korea, Japan, China, France and South Africa.

On the other hand, joint symposia supported by state agencies such as the Indo-France Symposium has enabled comprehensive discussions and an exchange of scientific expertise on various spheres of nanosciences and areas of application development. Furthermore, efforts have been made to connect with the Indian scientific diaspora—

Table 1 List of initiatives taken during the NSTI and NSTM to upgrade infrastructure facilitates

Years	Financial support for analytical facilities	Location
2003–2004	Design of New and Novel Nanoconstruction Tools	IIT, Mumbai, Maharashtra
	Construction of an optical tweezer for nanometer scale rhelogy	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 for materials Research, JNCASR, Karnataka
2008–2009	Augmentation of computing resources for simulation and data analysis	Inter University Accelerator Centre, New Delhi

Source of information: http://nanomission.gov.in/; The Energy and Resources Institute (TERI). 2009, A review of NT developments as applicable to developing countries, TERI Report

Table 2 List of post-graduates course in nanoscience and technology facilitated by DST

Years	PG Teaching programmes–Nano science and technology M.Sc./M.Tech	University and location
2007–2008	2 Year M.Tech. course	Anna University, Chennai–Annual Intake of 15 Students
	2 Year M.Tech. course	Indraprastha University, New Delhi–Annual Intake of 15 Students
	2 Year M.Tech. course	Jadavpur University, Kolkata–Annual Intake of 18 Students
2008–2009	2 Year M.Sc. course	Guru Nanak Dev University, Amritsar–Annual intake of 15 students
	2 Year M.Tech. course	SASTRA University, Thanjavur–Annual intake of 20 students
	2 Year M.Tech. course	Guru Jambheshwar University of Science & Technology, Hisar–Annual intake of 20 students
	3 Year Integrated M.Tech. course	University of Delhi
	3 Year Integrated M.Tech. course	Vellor Institute of Technology University, Vellore
	M.Tech. course	Aligarh Muslim University, Aligarh
	2 Year M.Sc. course on Nano Physics	Osmania University, Hyderabad
	M.Tech. course on Nano Medical Science	Amrita Institute of Medical Sciences, Kochi

Source of information: http://nanomission.gov.in; The Energy and Resources Institute (TERI). 2009, A review of NT developments as applicable to developing countries, TERI Report

Scientists and Technologists of Indian Origin Abroad (STIOs)–in other countries for the promotion of scientific networks and R&D collaborations. Other activities also include mechanisms to facilitate access to sophisticated research facilities and enabling academia-industry partnerships. A prominent example of international collaborations to strengthen ties between research and industry communities as well as government initiatives in the nano domain include Euro-India Net created under FP6 between EU and India. This forum also seeks to examine mechanisms for innovation and R&D in nanotechnology in EU and India. The tri-lateral initiative between India, Brazil and South Africa (IBSA) has also identified nanotechnology as a key focus area through with R&D in areas such as nanomaterials, nanosensors, as well as application oriented research such as hybrid solar cells, drug delivery systems are envisioned along with strengthening of human resources.

Other joint forums where R&D in nanotechnology has been emphasised include Indo-US S&T Forum, Indo-US High Technology Cooperation Group, Indo-German Committee on Science & Technology etc. [10].

Amongst State governments, those of Karnataka, Tamil Nadu and Haryana have figured prominently in promoting nanosciences and nanotechnology. Already an existing biotech hub, Karnataka with premier institutes IISc and JNCASR, which are amongst the designated CoE for nanotechnology R&D in the country, has been aggressively promoting nanosciences research in the country through various avenues. A vision group under Dr C.N.R. Rao, who also heads the NSTM Council has been created in the state and funds have been earmarked to develop the infrastructure needed to support nanotechnology related R&D. Bangalore, the capital city of Karnataka has been hosting an annual conference event- the Bangalore Nano which has

Table 3 Initiatives undertaken for human resource development and promotion under the NSTI

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 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		Fellowships granted to nano scientists; anchored by Jawaharlal Nehru Center for Advanced Scientific Research, Bangalore.
Advanced schools	To train researchers and generating the opportunity for them to develop hands on experience on sophisticated techniques, instruments and methods.	Nanomaterials Preparation, Characterization and Manipulation; IISc and JNCASR; Bangalore
		Science of Size Reduction, different routes of preparation, characterization of nano-materials and applications; S.N. Bose National Center for Basic Sciences; Kolkata
		Nanoscience and Nanobiology, Bangalore February 2007
Organising and supporting conferences, 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	Three international conferences on various aspects of nanoscience and technology in 2003, 2006 and 2008
		2 National Review and Coordination meetings in 2005 and 2007 to take stock of the R&D in India and evolve future directions
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 of information: http://nanomission.gov.in/; The Energy and Resources Institute (TERI). 2009. A review of NT developments as applicable to developing countries, TERI Report

attracted over the years, not only prominent researchers, national and international but also industry participation for developing applications in electronics, bio-medicine and manufacturing. In order to spearhead innovative lab scale R&D into commercial prospects, the conference hosts a Research-Industry Collaboration Hub (RICH) that acts as a platform for potential collaborative ventures between, investors, scientists and industry. On the whole, with claims that it has begun to host a significant proportion of the nations nanotechnology R&D, policy makers like M.N. Vidyashankar, Secretary, Department of IT, Biotechnology and Science and Technology, Karnataka envision Bangalore as the country's 'Nano city' [7, 30, 31].

Way back in 2002, Tamil Nadu, had also created a task force to investigate the potential of nanotechnology with the aim of enabling societal benefits. Recently in a fashion similar to that of Karnataka, in 2007 state officials were reviewing options for a nanotechnology policy and have also provided seed funds to state institutions such as IIT Anna University and Centre of Life Sciences at Bharathiar University to initiate R&D in this domain. In March 2008, the Tamil Nadu Technology Development and Promotional Centre sponsored a CII organized nanotechnology conclave that showcased the country's strengths in nanotechnology to international nanotech players [32]. Aside of this, state authorities have also desired to establish nanotechnology parks. For this they have roped in Taiwan's Hsinchu Science Park for the development of an adequate proposal and have also approached IIT Chennai and Anna University to help create the "park's ecosystem" that will house R&D, engineering and management institutes as well as companies, product manufacturers, investor, legal and administrative infrastructure [33]. The Haryana state government is also keen to develop nanotechnology related infrastructure in the state and with entrepreneur Mr. Sabir Bhatiya had conceived plans to develop the state as an S&T innovation hub. The goal is to attract public private partnerships and develop high tech R&D in the areas of nanosciences, biosciences materials and software products.

Private Participation in Nanotechnology in India: Role of Private Research Institutes and Industry

Of the various actors defining the technology landscape, manufacturers and the user firms that develop commercial products either individually or in collaboration with public funded research or in a variety of sectors for consumer use ideally constitute an important node. However, in India, whereas the rapid expansion of nanotechnology R&D has been witnessed in the public funded domain and at research institutes, industry involvement has been slower to emerge and is still in the nascent phase. In 2008 the size of the nanotechnology industry was estimated to be $200 million

[34]. Reasons for this include the vast monetary and infrastructural resources needed to undertake research of this kind as well as the relatively long gestation periods in translating laboratory work to commercial applications. In addition, the lack of clear regulatory guidelines as well as clear markets has prevented the enthused participation of industry involvement. Nevertheless, large and established companies involved in manufacturing such as Mahindra and Mahindra and Reliance and Tata Chemicals, Dabur are known to have assumed research in the nano domain to improve efficiency of their applications or products [35]. On the other hand, smaller companies and start-ups have emerged primarily as suppliers of nanomaterials as well as in the field of nano-biotechnologies and nano-medicine. As in the area of health, the involvement of small and mid sized companies in nanomaterial based water purification technologies has also emerged and is growing. Therefore, aside from facilitating the enhancement of industrial and manufacturing processes like catalysis, nanotechnology offers industry the chance to deliver products that contribute to societal benefits especially in the area of health and water. Overall, industry involvement in nanotechnology in India is slowly emerging with the fields of manufacturing, medicine, diagnostics, electronics and textiles are the prime areas for investment and R&D. As described earlier, the government's emphasis on public–private ventures in nanoscience and technology R&D in the NSTM might trigger several other such ventures for the development of specific applications.

Simultaneously industry associations like CII, ASSOCHAM and FICCI etc. have realized the significance of nanotechnology and are promoting R&D in this arena through fostering knowledge sharing and linking contemporary research and industries in nanotechnology in India. CII launched its Nanotechnology Initiative in 2002 with a focus on generating awareness, new technology adoption by industry and enabling existing products and processes using nanotechnology [32]. Under this initiative CII annually organizes Nanotechnology Conclave bringing together industry, governments and academia in partnership with other countries, the latest being organized in April 2010 at Chennai. FICCI in partnership with Ministry of Science and Technology annually organizes India R&D conferences. The 2008 R&D India Conference was held at New Delhi on the theme 'India R&D 2008: Nanotechnology–Science of the Future' [36]. ASSOCHAM also organizes dedicated sessions on emerging areas of nanotechnology and biotechnology, the latest being the 6th Global Knowledge Millennium Summit on Biotech and Nanotech for sustainable agriculture [37].

On the other hand, private institutions with ample funds and infrastructure are also emerging in India in the nanotechnology landscape. While institutes like Amrita Institute, The Energy and Resources Institute (TERI), Sankara Nethralaya have undertaken research in nanobiotechnology and nano-medicine, other private universities like Amity University and Amrita Institute of Nanosciences have started providing postgraduate courses in nanoscience and technology. The nascent but growing expansion of private research and teaching institutions in the field of nanotechnology could have a tremendous effect on the development of applications and volumes of postgraduates trained in the area of nanosciences and technology, thereby contributing to the progress of this technology in India much like private research institutions did in field of biotechnology.

R&D Activities in Public and Private Domains in Nanosciences and Nanotechnology

As observed in several countries, research and development in nanosciences and nanotechnology span a wide range of spheres. The bulk of the research in the public domain is funded through the NSTI and now NSTM headed by DST, followed by support by other agencies like CSIR, DBT, DAE, MNRE etc. Aside from this, research in private institutes has been mainly observed in the area of nanotechnology applications in the life sciences, whereas industry participation has largely been seen in the large scale manufacture of nanomaterials as well as in the health sector. The distribution of projects supported by DST through NSTI and NSTM across basic and applied research/product development is described below (Figs. 8, 9). Aside from funding R&D projects, support for building institutional and infrastructural capacity as well as human resources has also been provided by DST.

In publicly funded institutes, studies on the synthesis, characterization, processing and understanding of the unique properties of nanostructured materials has formed the bulk of the research in the nanoscience domain in India. A variety of nanomaterials such as metallic, metal oxide, semi-conductor, magnetic nanoparticles, quantum dots, carbon nanotubes and other nanocomposites, polymeric nanomaterials, nanofilms, nanowires, nano alloys, nanoporous solids have been undertaken. As expected, research on examining different route for synthesis of these materials, nanolithography, nanofabrication techniques has been a focus area in many institutions. In addition research for understanding the application of these materials particularly for industrial processes like catalysis has been stressed. Research and development of this kind forms a core part of several institutes particularly the designated CoE especially the Units of Nanoscience as well as several universities, including Central Universities of Hyderabad and Delhi as well as other state universities like University of Madras and University of Bangalore, University of Tezpur and several IITs including IIT, Guwahati.

On the whole, a significant number of projects have been sanctioned for examining fundamental dimensions of nano-scale systems with 33 R&D projects being sanctioned in the year 2009–2010 by DST. A good proportion of the investigations have also been oriented towards basic and applied research in the area of physics and chemical sciences. Some examples in chemical sciences include project on bimetal core–shell nanomaterials embedded in silicate sol–gel and polymer membrane modified electrodes and their application, the preparation of micro/nano MgO from bittern solution and evaluation of their surface characteristics as well as catalytic activity in some important organic reactions and in the sphere of green chemistry the development of nanostructured membrane for solvent recovery from organic solution. Interdisciplinary research is also in focus and investigations that draw from a variety of disciplines are being undertaken. For instance, a research project at the interface area of organic chemistry-biology-pharma, to develop glycobiology oriented nanotools for development of NEU-3 (human sialidase) inhibitors and explore their use for imaging of cancer cells has been initiated. Nanoscience research in the physical sciences encompasses fields like condensed matter physics and material science; plasma, high energy, nuclear physics, astrophysics and nonlinear dynamics as well as laser, optics, atomic and molecular physics.

Institutes and laboratories under CSIR and DAE have been particularly contributing to chemical, material and engineering sciences research in nanosciences in the above mentioned areas. Key focus of CSIR institutes in chemical and material sciences includes the synthesis and characterisation of a variety of nanomaterials ranging from inorganic nanoparticles, nanofilms, nanowires, nanoclusters and nanopowders to nanocomposites and novel polymeric materials. Some work has also been carried out in the area of the synthesis of nanomaterials from biological sources. In addition, efforts are also being made to produce nanomaterials in commercial scales at NPL. Key areas for applied research include development of nanomaterials for catalysis and for green processing, thin films for smart windows as well as wear resistant nanofiltration membranes. Major accomplishments listed by CSIR institutes in the R&D for industrial use includes lipid nanoparticle immobilization, carbon nanotubes using the DC arc discharge technique, nanocrystalline polymers with a variety of dopings for fabrication of fast response polymer based solid states and sensing devices. Technology interventions such as nanocrystalline ferromagnetic alloys, nano sized hydrographite powder for bone grafting have already been developed for commercialization whereas technologies under development include nanocrystalline ferro magnetic alloys, biomimetic synthesis of nano sized hydrographite powder for bone grafting etc. [28]. CSIR labs actively participating in this research include National Chemical Laboratory (NCL), Pune; National Physical Laboratory (NPL), New Delhi; Central Glass AND Ceramic Research Institute (CGCRI), Kolkata; North East Institute of Science and Technology (NEIST), Jorhat; Regional Research Laboratory (RRL), Bhubhaneshwar etc.

DAE, on the other hand, has extended its research in the Chemical and Material Science together with engineering sciences to the domain of nanoscience and nanotechnology. Work undertaken at these institutes encompasses aspects of molecular engineering of materials and understanding the processes at atomic and molecular level to help design better applications; synthesis of nanomaterials including nano-ceramics, nano-ionics, nanocomposites as well as oxides, bi-metallics, nano-structured catalysts in micro and meso-porous hosts. DAE has also focused towards developing new characterization tools for nanomaterials and nanodevices and was in the process of developing an intense slow positron pulsed beam using an electron linac to facilitate study of unexplored areas in positron chemistry. Their application oriented R&D focuses on areas of research such as development of nanomaterial coatings to prevent corrosion and increase efficiency of reactors and of

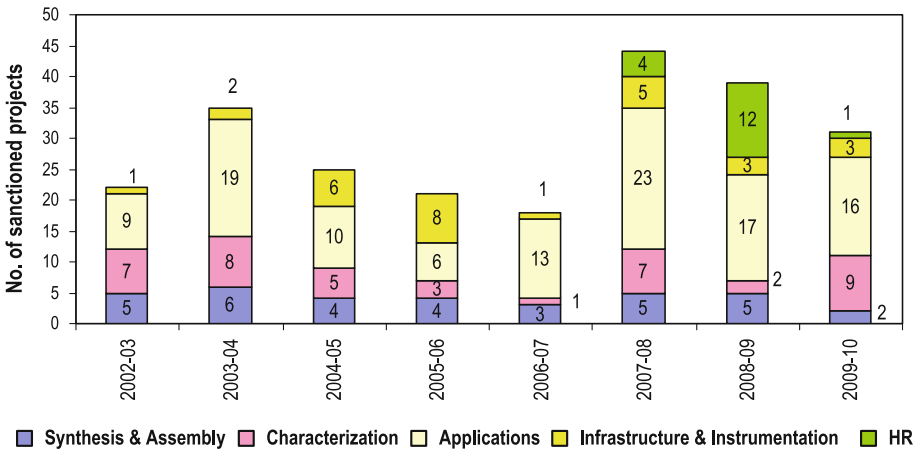

Fig. 8 Distribution of projects supported by DST through NSTI and NSTM across basic and applied research/product development and other areas. Source of information: http://nanomission.gov.in and http://dst.gov.in/scientific-programme/ser-serc.htm

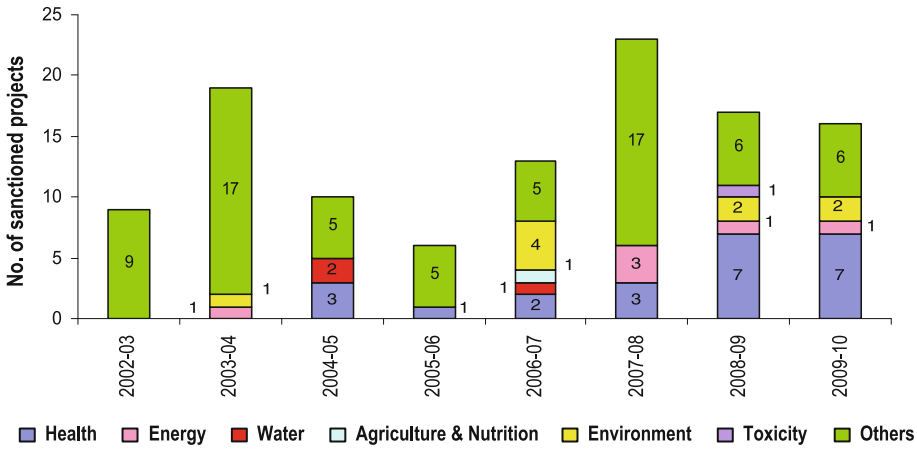

Fig. 9 Distribution of application oriented R&D projects supported by DST through NSTI and NSTM across different sectors and other areas. Source of information: http://nanomission.gov.in and http://dst.gov.in/scientific-programme/ser-serc.htm

nano-particles with improved efficiencies for application in radioactive waste reprocessing [29].

Aside from research institutes several industries are also involved in the synthesis and the large scale manufacture of nanomaterials either as raw materials for R&D or for development of specific applications. Specific nanomaterials being developed by industry include nanocrystalline lithium iron phosphate used in making the electrode for Li-ion batteries produced by United Nanotechnology Products, Kolkata and carbon nanotubes and carbon nanofibres produced by Monad Nanotech Ltd., Mumbai and Innovation Unified Technologies, Mumbai. Table 4 describes some companies involved in the manufacturing and supply of various nanomaterials.

Application of nanomaterials (electrically conducting, semi-conductor and others) in the sphere of electronics and information communications has been undertaken by several institutes. Some key areas of interest include development of nanomaterials for sensor, magnetic and opto- electronic, LED applications, thin film transistors, spintronics and quantum infomatics. Research on use of nano metals and alloys for fabricating interconnects in nanoelectronic applications and creation of nanodeices is also prevalent. R&D in all of these areas is being undertaken in several institutes including Centre for Materials for Electronics Technology (C-Met, Pune), Jadavpur University, IIT, Kanpur, IIT Kaharagpur, IIT Bombay, IISC Bangalore, University of Delhi, New Delhi and Visvesvaraya National Institute of Technology (VNIT) Nagpur. Among industry Cranes Software International Ltd. Bangalore is working on MEMS applications.

In the area of energy applications government supported R&D has included the development of nanomaterials -metal oxide nanoparticles like TiO2, CuO and ZnO as well as other materials such as semiconductors, nanotubes and mainly for photovoltaic applications such as poly crystalline, dye sensitized cells, thin film solar cells have been assumed in institutes like NPL, New Dehi, IIT, Kanpur, IIT Bombay, IISc, Bangalore etc. Some of these materials like TiO2 and nanotubes have been investigated for their application in hydrogen production whereas graphitic nanofibres and Magnesium alloys are being examined for the purpose of hydrogen storage. Emphasis has also been laid on developing hybrid solar cells with materials like nanotubes, CdTe and silicon at IACS and Jadavpur University, both based in Kolkata as well as Anna University, Chennai. Research on efficient lighting systems using GaN nanocrystalline films is also currently ongoing in Jadavpur University, Kolkata.

DAE funded institutes are also working on the development of materials like carbon nanotubes, metal hydrides etc. for hydrogen storage. CSIR laboratories have also been involved in research that applies to nanosciences in the energy sector through research on nanomaterials to enhance efficiency of super-capacitors etc.

The application of nanomaterials in the sphere of water treatment has received attention due to the significant challenge, developing countries like India faces in access to clean drinking water and therefore R&D in this sphere has garnered both public and private funds. Nanomaterials like nano-scale silver and carbon nanotubes are particularly being investigated for their role in water purification. While Banaras Hindu University together with Rensselaer Polytechnic Institute, USA have developed carbon nanotube filters for removal of bacteria in water, Bhaba Atomic Research Center (BARC) has also tested CNT filters developed in house for their efficiency. Some other promising research in this area includes ARCI's nanosilver based candle filter, the technology for which has been transferred to SBP Aquatech Pvt LTD, Hyderabad and IIT Chennai's work on nano silver activated carbon block that is being co- developed and commercialised by Eureka Forbes in one of its water filter products. IICT, Hyderabad is also involved in research on nano-silver coated alumina catalyst for water purification.

Applied research is also being undertaken in the area of textiles and smart materials at IIT Delhi whereas in other

Table 4 Companies involved in the manufacturing and supply of various nanomaterials

R&D services	Suppliers/Manufacturers
Nanomaterials manufacturing (nano silver powder, nano gold powder, liquid gold, silver oxide, silver nitrate, TST)	Auto Fibre Craft (Jamshedpur)
Equipments for textile waste water recycling for dyeing and other processes	Mp3s Nanotechnology Pvt. Ltd. (Mumbai)
State of art carbon nanotubes and related products and services	NanoFactor Materials Technologies (Bangalore)
Nanomaterials manufacturing (expertise in nanomanipulation and nanopositioning technology	Qtech Nanosystems (Bangalore)
Production of nanoparticles using patented technology	NanoBio Chemicals India Pvt. Ltd. (Belgaum)
Production of nanotubes, SWCNT′s, MWCNT′s, nanoparticles	NANOSHEL (Haryana)
Surface coatings based on nanotechnology (anti-corrosive coatings for metals, coatings for ceramic tiles and sanitary ware, water repellent coating for automotive windshields, coatings for construction glass, coatings for marbles and granites, coatings for natural stone), nanomaterials for paints	United Nanotechnologies Pvt. Ltd. (Kolkata) ICAN Nano, Kolkota
Ultra low cost MWCNT1-3 Nano beads, nano fibers, fibrous carbon nano size metals and porous carbon gas diffusion fuel cell electrodes. It is the first Indian company to produce carbon nanomaterials in India at commercial level	Monad Nanotech Pvt. Ltd. (Mumbai)
Supply small and bulk quantities of carbon nanotubes, especially useful for fuel cell and energy storage related application	Innovations Unified Technologies (Mumbai)
Working on inorganic nanoparticles	Tata Chemicals Innovation Centre (Mumbai)

Source of information: various sources

research the development of nanocomposites for tyre applications is also been funded. Aside from this, industry is also involved in supply of equipment necessary for undertaking R&D in nanosciences and technology.

Nanoscience and Technology in the Life Sciences

Research that involves the application of nanosciences and nanotechnologies in the field of life sciences has assumed considerable proportions since the commencement of the nanotechnology initiatives in India. The areas under the life sciences that has witnessed the most significant funding and R&D interest amongst nanoscientists has been in the broad field of what is known as nanomedicine which itself includes several areas such as targeted drug and gene delivery (therapeutics), diagnostic systems and biosensors as well as the use of biomaterials for various applications including regenerative medicine. Aside from nanomedicine, research at the cross roads of nanosciences, molecular biology and biotechnology, agricultural sciences, environmental sciences and toxicology has also been undertaken. The growing prominence of R&D in the area of nanomedicine and nanobiotechnology is derived from India's existing strength in the fields of pharmaceuticals and biotechnology. R&D in both the public funded institutes and industry especially in the pharmaceutics domain has been driven by the desire to use nanomaterials to improve their product portfolio and capture new markets–by either enhancing the efficacy of existing products or developing new nanomaterial enabled drugs. The perceived societal benefits that R&D in nanomedicine can provide in the health sector together with the economic opportunity it provides the pharmaceutical sector to leverage its strength in generic has led to both state aided funding as well as industry participation in this domain. Several of the state agencies including DST, DBT, ICMR, CSIR and DRDO are involved in funding R&D in the area of nano-biomedical sciences.

Nanoscale systems and drug delivery: Amongst the various areas under this domain, R&D in the field of using nanomaterials for drug delivery has witnessed great interest as these applications can facilitate sustained release of drugs and their targeted delivery to diseased parts of the body and also improve the bioavailability of drugs. R&D within this area of research is being assumed in several public and private institutes as well as industry and is also receiving the significant support from government agencies. As early as 2003–2004, projects on the development of bio-polymeric nanoparticles for drug delivery as well as study of molecular motors for nanomolecular switching and targeted drug delivery were undertaken by Jawaharlal Nehru University and the CSIR laboratory, Central Scientific Instruments Organisation, respectively. CSIO has also been researching on the potential of using carbon nanotubes for drug delivery with backing from DIT. Amongst the diseases that are being targeted by the nanoscale drug delivery approach, a large proportion of the R&D is oriented towards the therapeutic treatment for cancer, mainly because this disease is emerging as the one of the most serious afflictions amongst developing

country populations. Some other important DST supported research undertaken for in this area include the synthesis and characterisation of nanospheres for treating neuroendocrine tumours at AIIMS and drug delivery using magnetic PLGA nanoparticles for breast cancer treatment at IIT Bombay. Investigations on the development of novel drug carriers and nanoparticulate formulations as well as the assessment of their efficacy towards treating tumours is also ongoing in many public and private research institutes such as IACS and Manipal College of Pharmaceuticals. Research on targeted therapy using nanosystems for treatment of Multiple Myeloma, cancer of the plasma cells at Medical College, Calcutta has been supported by DBT in addition to studies on nanoparticulate drug delivery for curing hepatic cancer. Another interesting area of research involving nanoparticple mediated or encapsulated siRNA for targeted delivery to and treatment of cancer cells has also been initiated at IIT, Guwahati and Aligarh Muslim University, Uttar Pradesh. IIT, Guwahati is also working on biodegradable nanocarriers for targeted drug delivery and other nanomaterials with therapeutic implications. On the other hand a project on the formulation and evaluation of nanoparticulate delivery systems for peptide drugs has also been undertaken at the Institute of Chemical Technology, Mumbai while the potential for nanoparticle aided delivery of bioactive molecules of pharmaceutical interest is ongoing at the Institute of Genomics and Integrative Biology (IGIB). In a growing trend of financial support to collaborative R&D ventures, joint R&D at IIT, Chennai, Institute of Life Sciences (ILS), Bhubaneswar and Vision Research Foundation, Chennai has received funds in 2006–2007 for investigating the efficacy of drug laden biodegradable nanoparticle for treating cancer of the eye, retinoblastoma. In addition to these institutes, nanomaterial drug delivery for treating retinoblastoma has also been funded by ICMR at Sankara Nethralaya. Other projects supported by ICMR are described in Table 5. Another joint project between AIIMs and IIT, Delhi on the development of nanoscale systems for macrophage targeting was also backed by DBT.

Research in the area of drug delivery and nanosystems has also been undertaken for other ailments like inflammation of lungs, Alzheimer's disease and diabetes, the latter ongoing at the premier institute for pharmaceutical research, the National Institute of Pharmaceutical Education and Research (NIPER). In efforts to combat diseases endemic to developing countries like India, research in the area of nanodrug delivery for tuberculosis and visceral leishmeniasis has been initiated at AIIMS and H.S.G Vishwavidhyalaya Sagar Institute. Another study on the ability of lipidic nanoparticles in the treatment of malaria has also been supported by DBT. Other institutes involved in R&D associated with nanomaterials and drug delivery systems are Jamia Hamdard University at Delhi and Patel Pharmaceutical Education and Research Development at Gujarat.

Simultaneously, R&D on the development of materials for drug design and pharmaceutical applications include polymer composites, peptide conjugated hyperbranched/dendretic polymer nanocarriers, nanoemulsions and suspensions at institutes namely, Rangaswami College of Technology, Rajiv Gandhi Center for Biotechnology and Bharathidasan University, all located in Southern India. Recently the University of Calcutta and the Institute of Haematology and Transfusion Medicine in West Bengal together with the University of Hyderabad gold nanoparticles were also sanctioned funds by DBT for examining the role of gold nanoparticles in drug delivery and diagnostics.

Amongst the CoEs, IIT Bombay and Amrita Institute for Nanosciences are involved in R&D for drug delivery in significant way. IIT Bombay's research in the nano domain in life sciences is being undertaken in both fundamental and applied aspects through a DBT funded project "Nanobiotechnology for therapeutics: fundamentals and

Table 5 List of nanotechnology projects that have received financial aid from ICMR

Project	Institute/Location	Years
Oral delivery of cyclosporing, an immunosuppressive peptide by entrapment as Liposomes and nanoparticles	Al-Ameen College of Pharmacy, Bangalore	2005–2008
Nano particle delivery of bioactive constituents and drug by supercritical fluid system	Central Food Technological Research Institute, Mysore	2007–2010
Solid lipid nanoparticles as surrogate carrier for bioactive agents	Jamia Hamdard University, New Delhi	2005–2008
Nanoparticle mediated drug therapy to the brain for the management of Alzheimers disease	J.S.S.College of Pharmacy, Ootacamund	2006–2009
Treatment of visceral leishmaniasis with engineered nanoparticulate carrier containing amphotericin B	Dr.Hari Singh Gour Vishwavidyalaya, Sagar	2006–2009
Design development and evaluation of nanoparticulate drug delivery system of antiviral drugs for improvement of oral bioavailability	M.S.University of Baroda, Vadodara	2006–2007

Source of information: http://www.icmr.nic.in/projects/projectsanc2002–2007march.htm, The Energy and Resources Institute (TERI). 2009, A review of NT developments as applicable to developing countries, TERI Report

applications". Specifically, their work on magnetic nanoparticles for drug delivery has been undertaken to improve the effectiveness of cancer treatment. The magnetic particles attached with drugs can be concentrated into desired area by applying an external magnetic filed and followed by exposure to AC magnetic filed, which might facilitate a more effective therapeutic outcome. Their research on folic acid targeted stealth liposomes containing drugs and magnetic nanoparticles is perceived as an efficient mechanism for drug delivery and treatment of cancers. Other work in the institute involves developing anti-tubular drug loaded surfactant nanoparticles for treating pulmonary tuberculosis. Surfactant nanoparticles themselves are excellent candidates for alleviation of respiratory distress syndrome in adults and neonates and this approach for drug delivery is considered particularly non-invasive. Optimisation of surfactant type for superior reach in alveoli and drug release is ongoing.

On the other hand, The Amrita Centre for Nanosciences (ACNS), Kochi is currently working on a project on Novel Nano Delivery Carrier for Systemic Control and Release of Parathyroid Hormone for Treatment of Bone Diseases. The scope of this proposal is to identify a novel delivery method for either systemic or oral application that could result in the release and bioavailability of PTH 1–34 peptide in a sustained and prolonged manner and also to overcome the challenges of the traditional method of treatment (i.e. daily injection from several weeks to several months). In addition, the ACNS also proposes to work on Novel Biodegradable Thermo-Responsive Nano-Vehicles for Cancer Drug Delivery Applications. The institute is also interested in research on Novel Biodegradable Thermo-Responsive Nano-Vehicles for Cancer Drug Delivery Applications. This research incorporates novel nanoparticles such as gold or iron-oxide into the thermo-responsive polymeric particles which can produce heat under irradiation with radio-frequency waves. Through this research they propose to overcome the difficulties in the existing application of thermo-responsive polymers for in vivo drug release.

Several research groups in Institute of Genomics and Integrative Biology are involved in synthesis as well as in vitro and in vivo activity studies of novel, efficient and non-toxic nano-delivery systems based on cationic polymers and peptides as well as nanoparticle-mediated DNA delivery. In addition, mechanistic studies on packaging processes of different DNA nanocarriers based on polymers and peptides using AFM and correlating their intracellular delivery efficiency with packaging is also being carried out. It is perceived that these approaches are likely to lead to design of new materials for targeted delivery. Also in the area of drug delivery involving nanotechnology SASTRA University is working on projects such as 'Development of Dendrimer based Novel Nano Drug Delivery System for cancer' and 'Novel Nanoparticle Based Targeted Drug Delivery System for the Treatment of Rheumatoid Arthritis'. Furthermore, the Pharmaceutics department at NIPER, Chandigarh has initiated research in the area of Nano-biopharmaceutics with a focus on drug targeting and gene delivery. The pharmaceutics department is involved in the design of biodegradable nanoparticles for pharmaceutical applications and the development and evaluation of nanoparticles for delivery of estradiol, antioxidants and insulin.

Tissue engineering and regenerative medicine: The development of nanomaterials for biomedical applications especially in tissue engineering and regenerative medicine is also emerging in India. DST in the year 2005–2006 funded the National Metallurgical Laboratory, a CSIR institute at Jamshedpur for their research on developing nanocomposites for tissue engineering and followed it up by funding similar research at SASTRA University the next year. In 2006–2007, SASTRA also received support from SERC program for work on the development of biodegradable nano-structured vascular grafts which aims to develop 3-D cardiovascular grafts & artificial skin using nanomaterials. Their other work in this area involves developing novel three dimensional nanocomposites for bone tissue engineering. DBT has also supported research in tissue engineering at various institutes which includes the development of polymer-ceramic nanocomposites with cell and growth factors for applications in bone tissue engineering, fabrication of nanobiomaterials for tissue engineering as well as development of nanocomposite scaffolds that are biodegradable. Joint R&D for the development of scaffolds that are based on nanofibres for the purpose of hepatic tissue engineering is also been undertaken at IIT, Guwahati and National Centre for Cell Science, Pune.

Regenerative medicine dealing with regeneration of tissues and organs using nanomaterials is an important research area in India. The Amrita Centre for Nanosciences (ACNS) at Kochi is currently developing a nanostructured scaffold based approach for tissue regeneration. This involves considerable in vitro cell culture studies including stem cell culture studies to understand the cell-nanomaterial interactions and the nature of cell attachment and proliferation on nanomaterials. The Centre is currently working on a project on 'Preparation of Novel Biodegradable Chitin Scaffolds with Hydroxyapatite/ZnO Nanoparticles for Wound Dressing Applications'. The primary objective of this project is to develop such gels, scaffolds based on chitin with HAp/ZnO nanoparticles for wound tissue engineering applications. The focus is on research into such natural scaffold-based nanodressings for rapid healing and preventing inflammation and infection. In addition, this institute has also received DBT support for research that uses cell targeted nanomaterials for 'Theragnostics Re-Generative Medicine and Stem Cell Research'.

Nichi-In Center for Regenerative Medicine (NCRM), based in Chennai, India, is an Indo-Japan joint venture institute that carries out research, training and clinical applications-protocol development in regenerative medicine, with emphasis on stem cells, progenitor cells and autologous adult cells with regenerative capability to take them to clinical application. NCRM has been working closely with 240 different nanomaterials and technologies in specialties such as ophthalmology (corneal regeneration), orthopaedics (cartilage injury repair), and haematology (expansion of hematopoietic stem cells).

Development of nanomaterials for therapeutic applications and other biomaterials: Other R&D on nanomaterials in the context of therapeutic applications includes synthesis of nanocrystal silica from rice husk for use in biomedical applications and nano-sized hydrographite powder for bone grafting at CSIR laboratories. The development of nanocrystalline calcium phosphates for bone and dental implants is ongoing at Anna University. Studies on the development of silica nanocomposite biomaterials as well as nanotube reinforced hydroxyapatite Polyether ether ketone nanocomposites for biomedical applications are also underway in IIT Kanpur. At CSIR institute, NCL, Pune researchers are working on fabricating polymeric nanofibres that are biocompatible for wound healing whereas another CSIR laboratory, IICT, Hyderabad is involved in the synthesis of multifunctional and biodegradable polymer nanocomposites for various applications.

Nanomaterial based diagnostics, nanosensors and nanodevices: The use of nanomaterials in the field of diagnostics, the development of nanosensors and devices is actively progressing in India as especially in the latter case nanomaterials provide great opportunities to improve the functionality and service of devices and adjust their properties for better biological compatibility. One of the key thematic areas of R&D at IIT Bombay is micro-devices for cardiac use and there is considerable activity currently in fabricating devices/structures with critical dimensions in the sub 100 nm regime and sub 50 nm regime. The aim is to use molecular materials like conjugated polymers with immobilized proteins and nucleic acids for fabricating new device structures, electrodes for molecular electronics, for DNA synthesis, sensors etc. The nanotechnology facility at the Indian Institute of Sciences, Bangalore also conducts research work in the area of nano devices. Researchers at IIT Bombay have developed the biosensor "iSens", a point of care assay system that detects molecular markers for myocardial infraction that typically are indicators for heart attacks.

Nanotechnology research at Central Scientific Instruments Organizastion (CSIO) involves research activities in the areas of molecular electronics, nano-robotics, nano/molecular switches, nano-sensors, MEMS micro diagnostics targeted drug delivery, and biomolecular electronics & nanotechnology. One important area of research is molecular motors such as actin-myosin that can be used for molecular/nano switching, targeted drug delivery and nano-robotics. Moreover, carbon nanotubes (CNTs) are also being studied for bio-nano sensors and drug delivery applications by their interfacing with bio-molecules. Techniques have been developed for reliable and fast dispersion and functionalization of CNTs whereas work on the bio-activity of bio-interfaced CNTs and their toxicity is in progress other research on quantum dots is being undertaken for diagnostic applications. CSIO has also developed a nanotechnology based diagnostic kit for tuberculosis that is claimed to be portable, inexpensive and efficient to use. On the other hand, another CSIR institute, Center for Cellular and Molecular Biology (CCMB) also heads a large project on 'Nanomaterial and Nanodevices in health and disease'. Similarly, labs under DRDO have fabricated a nanosensor based typhoid diagnostic kit.

In other research, semiconductor nanocrystals as well as dendrimer encapsulated gold nanoparticles are also being studied for their use in the diagnosis of cancer where as gold nanoparticles together with and quantum dots diseases are being investigated for their role in facilitating diagnostics for tuberculosis.

Interaction of nanomaterials with human systems and toxicological studies: Aside from the R&D on drug delivery, diagnostics and use of nanomaterials in other therapeutic applications, research on developing an understanding of the interactions and the effects of nanomaterials on cells and tissues as well as ecosystems have been initiated in India. In addition some specific research groups at IITR, IGIB and Amrita Centre for Nanosciences are involved in studying the toxicological impacts of specific nanomaterials. Research in this sphere has been supported by DST including SERC as well as DBT. The Nanomaterials Toxicology Group of the Indian Institute of Toxicology Research (IITR) is at present conducting research in the area of safety/toxicity evaluation of nanomaterials, devising new methods and validation of existing techniques that can be applied for safety/toxicity assessment of ENMs and nanodevices. Its research competencies in nanotechnology include synthesis and detailed characterization of nanoparticles, investigating interactions of different types of nanomaterials with biological systems (from whole organism to molecular level) in order to evaluate their toxicity, in vitro and in vivo toxicity assays addressing issues of cytotoxicity, genotoxicity, immunotoxicity, dermal toxicity, neurotoxicity, reproductive toxicity, biodistribution, metabolism, elimination and ecotoxicological impact.

IGIB also in addition to its research on drug delivery is also applying a toxicogenomic approach to observe and rationalize the toxicity effects of gold, silica and other nanoparticles in both cultured cells as well as in a zebrafish

Table 6 List of projects supported by various agencies on issues of toxicity, environmental and health implications of nanomaterials

Agency/ Year	Title	Locations
DST 2007–2008	Fate of nanomaterials in biological systems	Indian Institute of Toxicology Research, Lucknow
DST 2008–2009	Ferric pyrophosphate nanoparticles: Feasibility, bioavailability and toxicity assessments	St. John's Research Institute, Sarjapur Road, Bangalore
SERC 2007–2008	Studies on the characterization and toxicological effects of engineered carbon nanoparticles in human cell lines and animal models	Centre for Environment, Instt., of Science & Technology, Jawaharlal Nehru Technological University, Hyderabad
DBT 2007–2008	Studies On Ecotoxicology Of Engineered Nanoparticles In Selected Marine Organisms	Sathyabama University, Chennai
	Toxicological Studies Of Newly Developed Nanomaterials Of Medical Importance Using In Vivo And In Vitro Model Systems	Indian Institute Of Chemical Technology, Hyderabad

Source of information: http://nanomission.gov.in, http://dst.gov.in/scientific-programme/ser-serc.htm and http://dbtindia.nic.in/index.asp The Energy and Resources Institute (TERI). 2009, A review of NT developments as applicable to developing countries, TERI Report

Table 7 List of industry players in the sphere of nanotechnology and life sciences

Manufacturer	Product	Other details
Dabur Research Foundation (Uttar Pradesh)	Nanoxel	Contract research
		Co-development of nano-polymer & liposome based drug delivery systems
		Formulation development of solid & injectable dosage forms for cytotoxics
Bharat Biotech (Hyderabad)	Estrasorb	First to launch nanobiotech product in estrogen therapy in association with Novavax. The drug is loaded in a micellar nanoparticle formulation
SSB Technology (Mumbai)	Nanocid	Tie-up with Tide Waters, Iran to market its products under the brand Nanocid
Veeco Instruments Inc. (Bangalore)	Nanoman	Most advanced high-end SPM for direct nanoscale manipulation and nanolithography Digital Instrument CP-IITM SPM NT1100, a bench top-Optical
		Profiler: subnanometer Surface roughness and millimeter-scale steps with high resolution, repeatability and speed
Lifecare innovations (Haryana)	Fungisome-Liposomal Amphotericin B Fungisome gel	First tropical liposomal amphotericin B nano-drug in the world
Nano Cutting Edge Technology Pvt Ltd–Nanocet® (Mumbai)	Silver-Nano gel, Gold- Nano gel, Biostabilised Iron-Palladium nanoparticles	Material Science and Engineering through Biology. A variety of semiconductor and transition metal nanoparticles have been synthesized using a repertoire of metal interacting microorganisms. These methods are eco-friendly and less energy–intensive as compared to conventional methods
Velbionanotech (Bangalore)	Bionanochip, nano medicine, nano material, Microdoctor, nano sensors and herbal medicine. Designing DNA based drug for heart disease, kidney stones, AIDS, cancer, cosmetic generic products	Ranked Asia's top 100 nanobiotech by Red Herring, 2005
Centre for Advanced Research & Development (Bhopal)	Nanoblaster technology–(a new technique to blast cancer cells in the human brain and other parts of the human body)	'Rational field quantum magnetic resonance' (RFQMR) generator'-noninvasive technique to regenerate dying tissues in the body that cause serious disabilities in arthritis patients. Technique to detect cancer at early stage
Panacea Biotech (New Delhi)	Nanoparticle-mediated delivery of non-stroidal drug to eye	–

Source of information: various sources

Table 8 List of patents filed in the area of nanosciences and nanotechnology at the IPO

Patent number	Date of filing	Title of invention	Applicant name
Health			
212068	11/07/2000	A pharmaceutical composition based on nanoparticles of polymeric michelles containing paclitaxel	Dabur India Limited
220861	29/03/2004	A suspension of nanoparticulates of an antimitotic drug	Crititech, Inc.
219691	08/06/2004	Pharmaceutical nanoparticulate composition of a tachykinin receptor antagonist	Merck & Co., Inc
222450	17/01/2000	Nanoparticles (dnp) for the delivery of active principle(s)	Flamel Technologies
222300	05/05/2003	Preparation of agar bionanoparticles	Gorur Amita
Energy			
201822	18/03/2003	A process for the manufacture of a nano composite for harnessing solar energy	Indian Institute of Technology
197946	13/06/2001	Carbon nanotube flow sensor and energy conversion device	Indian Institute of Science
Water			
212665	09/11/2001	A method for removal of nano-sized pathogens of a size from 20 nm to 500 nm from water	The Procter & Gamble Company
Other areas			
199561	20/06/2003	A method for producing metal oxide particles having nano-sized grains	Very Small Particle Company Pvt. Ltd., An Austrailan Company
199763	27/08/2003	Process for producing nanometer grade powders	Anshan University of Science and Technology
207748	17/11/2003	A nanoporous receiver element for use in thermal mass transfer imaging and a mass transfer thermal imaging method	Polaroid Corporation
206369	17/09/1998	A process of preparation of nanosized metal molybdate particles	Indian Institute of Technology
219069	23/11/2005	Method for making a nano-particulate medium	Coventry University
218357	29/11/2000	A process for the preparation of a nanosized noble metal catalyst useful for the selective preparation of aliphatic diol	Council of Scientific and Industrial Research
208589	12/10/2004	Process for preparation of self micro/nano emulsifying systems and compositions thereof	1)Patravale Vandana Bharat 2)Khan Imran Ahmad
216035	27/04/1998	An improved process for the production of high-purity nano-crystalline alumina powders	Council of Scientific and Industrial Research.
217800	16/01/2004	Process for preparing nano-powders and nano-particle loose aggregates powder	Anshan University of Science and Technology
218201	26/12/2000	An improved process for the preparation of nano-composite cathode materials for high energy density rechargable lithium batteries	Council of Scientific and Industrial Research
212645	26/12/2000	An improved process for the preparation of semiconductor nanocluster or polymer composite useful for the applications in nonlinear optics	Council of Scientific & Industrial Research
220793	28/12/2001	A process for the manufacture of nano-size pure and doped bivalent metal sulphide powder	Council of Scientific & Industrial Research
197755	04/01/2001	A method of making a supported fluid separation membrane of nanopore structure	Indian Institute of Technology
216535	05/11/1999	A process for making silicon carbide -mullite-alumina nanocomposite	Council of Scientific and Industrial Research
222331	05/07/2005	A discrete tubular or discrete spherical peptide nanostructure and the method of preparing thereof	Ramot at Tel Aviv University Ltd
215660	28/12/1999	An improved process for the preparation of metal nano particles	Council of Scientific & Industrial Research

Table 8 continued

Patent number	Date of filing	Title of invention	Applicant name
208960	17/09/1998	A process of preparation of nanosized metal vanadate particles	Indian Institute of Technology
216873	17/09/1998	A process of preparation of nanosized metal oxide particles	Indian Institute of Technology
223694	16/09/2004	Self-aligned nanotube field effect transistor and method of fabricating same	International Business Machines Corporation
226024	13/09/2005	Filtering device incorporating nanoparticles	Beplate, Douglas, K
216499	21/10/1998	A nanocomposite magnetic material	Santoku Corporation
225532	03/10/2005	A composition comprising a synthetic polymer and a process for the preparation of a synthetic polymer nanocomposite material	Polymers Australia Pty. Limited
221787	01/09/2004	A process for generating colored nanolithography on glass and plastic substrates	Council of Scientific and Industrial Research
215335	02/02/1998	A substrate comprising layers of diamond like carbon and diamond like nanocomposite composition	N. V. Bekaert Sa
223617	20/03/2002	A process for the preparation of Fe-based ultrasoft nanocrystalline ferromagnetic alloys	Council of Scientific and Industrial Research
208563	24/05/2004	A membrane and a method for forming nanowindows in a substrate	Starmega Corporation
218001	19/03/2001	An improved process for preparation of ultrafine and nanocrystalline compounds	Council of Scientific and Industrial Research
218355	23/03/2001	A process for the preparation of a nanosized colloidal metal particle	Council of Scientific and Industrial Research
195172	08/12/1997	A process for preparation of ultrathin nanofilms of metals	Council of Scientific and Industrial Research
218499	05/05/2003	Preparation of Oligosaccharide bionanoparticles from Moringa Oleifera Lam	Sambandam Shanmugasundaram
199123	11/05/2001	A method of manufacture of carbon nanotubes and such tubes whenever so manufactured	Indian Institute of Technology
224812	28/03/2002	A process for the preparation of metal sulfide nanoparticles	Council of Scientific and Industrial Research
221909	30/07/2004	Method of making nanocrystalline inogranic based Zeolite	Abb Lummus Global Inc.
213016	10/05/1999	A nanodipersion of suitable composition	Ciba Specialty Chemicals Holding Inc
213605	11/05/2004	A novel process for production of nanoparticles using subcritical carbon dioxide	Indian Institute of Technology, Bombay
200204	22/12/2000	A process for the preparation of a zirconia nanopowder	Indian Institute of Technology
223013	25/07/2002	A portable arc reactor useful for producing materials such as fullerenes and carbon nanotubes	Council of Scientific and Industrial Research
214165	15/07/2005	Method and installation for making carbon nanotubes	Universite De Liege
228267	29/08/2001	A Process for the Preparation of Graphitic Nanofibers and Apparatus	Bipin Kumar Gupta
219111	03/09/2004	Polyurethane foam coated with silver nanoparticles	Indian Institute of Technology
210596	27/01/2000	Neonanoplasts produced by emulsion technology	M/S. Kimberly-Clark Worldwide, Inc
214524	09/04/2001	Method for making a nanoporous granular material and a detergent composition	The Procter & Gamble Company
210855	02/09/2002	Nanocapsules and process for its preparation	Mainelab
209516	11/11/2002	An iron-based rare earth alloy nanocomposite magnet and a method for producing the same	M/S. Neomax Co Ltd

Source of information: Indian patent office

model system. Amrita Centre for Nanosciences, Kochi research work in the area of nanotoxicology involves a comprehensive evaluation of different classes of nanoparticles including cytotoxicity, inflammatory response, cancer-causing potential or tumerogenicity, bio-distribution and excretion and on methods of mitigating the toxicity of nanoparticles.

Table 6 lists some of the research undertaken by different groups across the country in this area. Other research recently supported by DST involves investigations on the impact of the exposure to ferromagnetic nanoparticles on motor and cognitive behaviour in 6- hydroxydopamine in adult rat model. DBT, on the other hand, has recently provided financial assistance to JNCASR for a project that explores the cellular interaction of nanoparticles and its role in gene expression that has implications to applications like drug delivery and diagnosis.

Role of industry in the application of nanotechnology in the area of health and life sciences: R&D in the area of drug delivery has been a prime area of focus by the industry. Table 7 lists the applications being developed and research being undertaken by various industries in India.

Publications and Patenting Scenario in Nanotechnology in India

Publications in Nanotechnology Sector in India

During 1990–2007, of the 21000 publications in nanotechnology listed at Scopus database, the share of academia and government R&D institutions is about 48 and 28 % respectively. Industrial firms constitute about 1.3 % (80 % contributed by domestic firms, 20 % by foreign firms operating in India) of the total nanotechnology publications in India [38]. Some of the major academic institutions with high publication in nanotechnology are Indian Institute of Technology, Indian Institute of Science, Jadavpur University, University of Delhi and University of Pune etc. Of the government R&D institutions the major contributors are Bhabha Atomic Research Centre, Indian Association for the Cultivation of Science, Indira Gandhi Centre for Advanced Research, Saha Institute of Nuclear Physics, CSIR Labs (NCL, NPL, National Institute for Interdisciplinary Science and Technology, Indian Institute of Chemical Technology, Central Electrochemical Research Institute, Central Glass and Ceramic Research Institute, National Metallurgical Laboratory, National Aerospace Laboratories, Central Salt and Marine Chemicals Research Institute, Central Leather Research Institute, and Indian Institute of Chemical Biology). The firms in the industry which have made significant publications in nanotechnology include Reliance Industries, Sun Pharma Advanced Research Centre, Tata Chemicals Limited, Torrent Research Centre etc.

Patenting Activity

There has been a spurt in the intensity of patenting activity in nanotechnology in India in the recent years during 2001–2007 [38]. Indian patenting in nanotechnology at the USPTO, EPO, WIPO, INPADOC, abstracts of Japan and in granted German patents indicates that, of the total 167 patents, 39 % of the total patents are owned by the government institutions (64 patents), 27 % by the industry (45 patents), and 6 % by academic institutions (10 patents) [38].

Looking at the Indian nano patent landscape, of the 64 patents on nanotechnology granted by the Indian Patent Office from 1997 onwards, about 28 patents are owned by academic and scientific institutions, 24 patents by firms in the industry, and the remaining patents being owned by private individuals [39]. The scientific research institution owning majority of the patents include laboratories of the Council of Scientific and Industrial Research (CSIR). Among the academic institutions, the IITs have been the major contributors of nanopatents at the Indian Patent Office (IPO). The list of patents in nanotechnology is provided in Table 8. There have been patenting in nano applications in the developmental sector such as, health, energy and water. For example, in the health sector, Dabur India Ltd. owns a patent on pharmaceutical composition based on nanoparticles of polymeric michelles containing paclitaxel. Similarly, in the energy sector, IIT has been granted a patent on devising a process for the manufacture of a nano composite for harnessing solar energy.

Conclusions

There has been an increasing investment and policy support in nanotechnology in India in view of its potential in addressing key development challenges in sectors like, health, energy, water, agriculture etc. The innovation framework for nanotechnology in India includes a wide range of actor–research bodies, nodal ministries, planning bodies, industry, industry associations, financial institutions and civil society organizations. However, in the Indian context, the role of public sector research organizations and the policy support to nanotechnology has contributed to a large extent in shaping the trajectory of this emerging technology. Given that nanotechnology has application potential in a wide range of areas and services, the focus in India has been on harnessing it for promoting development in key sectors viz., health and life sciences, energy, water treatment, textiles etc. However, of all the sectors in which nanotechnology has found application potential in India and

in which research activities have been initiated, the sectoral system of innovation of health nanotechnology could be assumed to be at a somewhat advanced stage. Besides significant quantum of research activities that have been undertaken in nanotechnology in the health sector across a wide spectrum of research institutions and private organizations, the presence of a significant number of firms in the industry has enabled the development of this sector. The perceived societal benefits of undertaking research and development activities in nanotechnology in the health sector along with its economic potential has led to research focus in the areas of nanoscale systems and drug delivery, tissue engineering and regenerative medicine, nanomaterials for therapeutic applications and other biomaterials, nanomaterial based diagnostics, nanosensors and nanodevices, interaction of nanomaterials with human systems and toxicological studies. Further, there has been increasing public private partnerships in the context of interdisciplinary character of nanotechnology, its knowledge intensiveness and to foster industrially relevant products and process. Of the six joint institute industry projects under the NSTM, three have been developed specifically in the health sector. Thus, notwithstanding the challenges associated in engaging with this emerging area of science and technology the dynamics of the innovation trajectory of nanotechnology suggests that India stands on a strong platform to reap its benefits and address the developmental needs.

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Appendix

See Fig. 10.

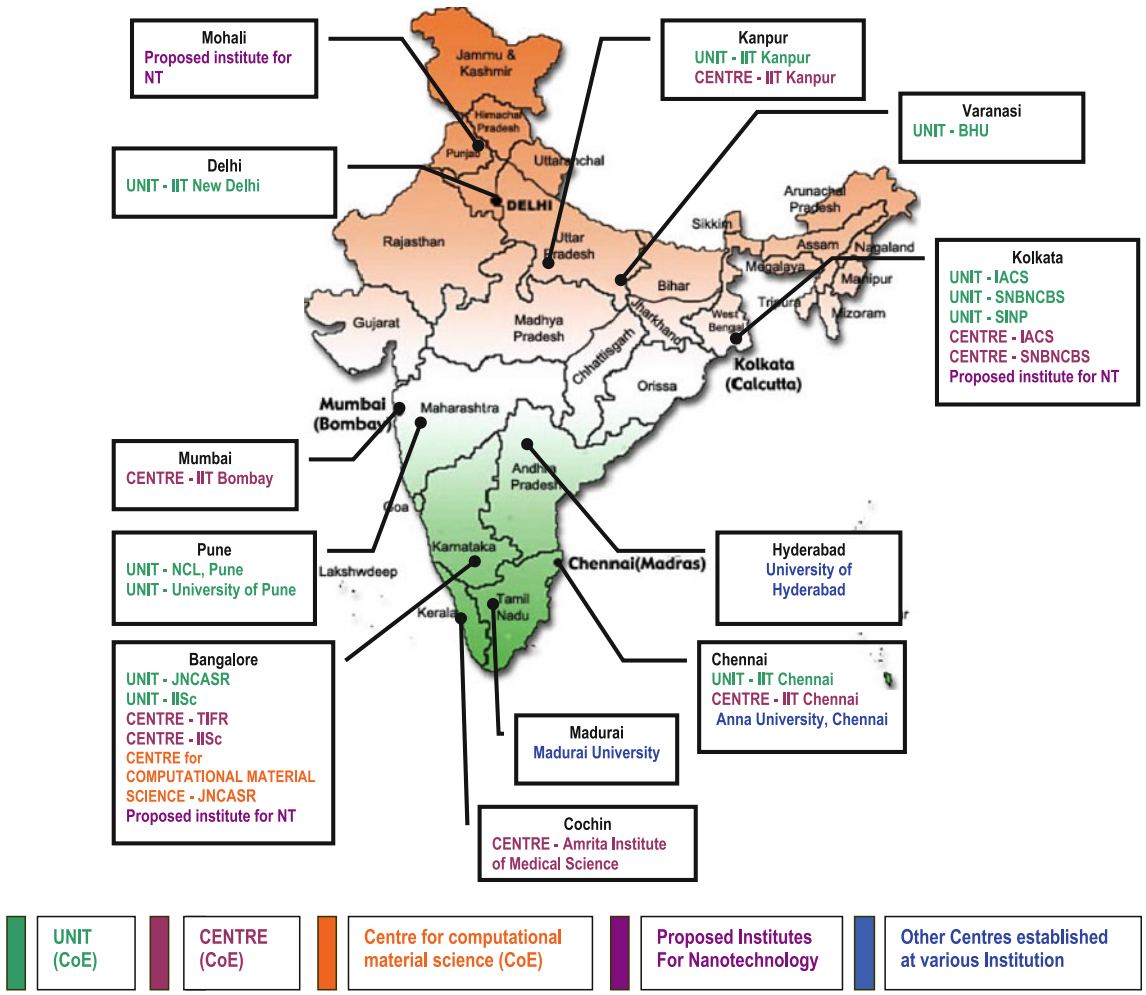

Fig. 10 Location of the Centres of Excellence and other centres established or proposed for nanotechnology in India. Source of information: The Energy and Resources Institute (TERI). 2009. A review of NT developments as applicable to developing countries, TERI Report. Source of map of India: http://www.indempan.org/image/india-map.jpg

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