# Executive Summary

This study was undertaken with the intention to explore and assess the developments surrounding nanotechnology in India. It investigates capacity creation, output and outcome of India's involvement in this field by examining policies, strategies, programs, funding, stakeholder's involvement, governance mechanism, etc. The study also examines policies and strategies of other countries and discerns 'positive outcomes' that can be adopted. The primary objective of the examination is to identify initiatives that have led to 'positive outcomes' so that those programs can be strengthened further, identify opportunities and gaps that if not addressed may impede the development and suggest plausible strategies for developing the nanotechnology research and innovation ecosystem and commercialization.

*Nanotechnology: the field, its complexity and challenges*

Nanotechnology involves developing the ability to control the shape, size, and chemical composition of structures in the 1-100 nanometers scale ($10^{-9}$ meter; one ten thousandth of a millimeter). For comparison, a human hair is approximately 80,000-100,000 nanometers wide whereas a strand of human DNA is 2.5 nanometers in diameter. Particles and structures of this size differ from their counterparts in the microscopic world in two fundamental aspects: the relative surface area of such structures increases enormously, and quantum effects occur. This results in significant modification of physical, chemical and optical properties leading sometimes to novel effects that can radically change process/product configuration. Development of sophisticated instruments has made it possible to manipulate and create novel materials and structures at the nano scale.

The pervasive potentiality of nanotechnology of being a generic, horizontal, enabling and/or disruptive technology with its potential to revolutionize a wide range of technological sectors, fields, application and process has generated a great deal of excitement worldwide. Nanotechnology is already making an impact in manufacturing, energy solutions, medicine, automotive, ICT, etc by enhancing the functionality/development of novel processes and products therein. For instance, in ICT applications the advantages are in enhanced power to compute and lower power consumption, low cost microprocessors with huge memory capacity and organic large area displays with much higher resolution. Nanotechnology is particularly appealing to developing economies such as India as along with the promise of improving the functionality of existing products/processes or creating new products, it can provide novel interventions in areas that are of pressing concerns i.e.

environment, water purification, agriculture, energy. Thus if properly addressed, nanotechnology can provide a 'window of opportunity' for developing countries to leapfrog and 'catch up' with the developed North.

Developing competency in this field is an immense challenge as it is a science intensive technological field which is highly interdisciplinary, capital intensive, requires sophisticated instruments, skilled interdisciplinary manpower, etc. The field is evolving and thus there is a large degree of uncertainty which creates ambiguity ranging from properly defining the field itself, developing regulatory framework that can address among others the risk aspects, and patent examination criteria's, etc. Creating competence requires factoring all these issues in the policy and creating institutional structures for implementation, regulation and standardization.

Governance of nanotechnology calls for strong linkages of the policy makers/funding agencies with the different stakeholders ranging from academia, industry to the public at large. It involves planning, funding prioritizing and facilitating the creation of knowledge base, development of research and innovation ecosystems, creation of supporting institutions and framework for technology regulation, skill development, IPR, risk and standards, etc. It also involves creating institutions for developing interfaces between upstream and downstream activities. One of the key issues in nanotechnology governance is regulation and risk mitigation which can lead to responsible technological development (address economic and social welfare without any adverse implications).

Uncertainty about the effects/potential impacts of this technology makes creating a regulatory framework, a challenging exercise. Nanotechnology governance is not a locale specific activity. It involves processes and involvement of multiple actors at national level which directly and indirectly shapes and gets shaped by nanotechnology development at international level. Therefore the issues of standardization, regulation, patentability and commercialization is not only country specific but are influenced by wider global factors. This calls for developing governance framework that is dynamic and can address international regulatory guidelines, at least guidelines applicable in major European and USA as these are major markets for high technology products.

*Learning from different countries*

The study has examined nanotechnology initiatives of different countries particularly USA, China, South Korea and to some extent activities in some Asian countries. Distinct models can be discerned from different countries approach to nanotechnology development. However, there are many commonalities in policies and strategies adopted by different countries. Possibly this commonality is due to the strong influence of US NNI: National Nanotechnology Initiative launched in 2001. One of its major influences is their 'mission oriented'/dedicated funding support which has been adopted by majority of countries in varying degrees. Countries have also created roadmaps for short term to long-term approach following NNI roadmap to a large extent.

Distinct features however, emerge in countries roadmap articulation/policy formulation and implementation. Countries with advanced scientific capacity and highly efficient innovation ecosystem are more ambitious; have an expansive approach and have programs to enhance capacity for nanotechnology intervention in different sectors. Among their central goal is to make their industry competitive particularly manufacturing competitiveness in different sectors through nanotechnology based intervention. Institutional mechanisms and support structures have been created to develop the research innovation ecosystem. Along with strengthening the existing institutional structures, new institutional structures are being created to accommodate nanotechnology. This model mainly observed in advanced OECD countries is also being followed to some extent in emerging countries such as BRICS countries. On the other hand, countries such as Sri Lanka, ASEAN countries with more constrained resources/scientific diversity are focusing on end user applications (directing focus on a specific problem in which nanotechnology intervention can make significant positive changes). For example, Sri Lanka directed focus on applying nanoparticles to improve adhesion of tyres to the road, reducing the stopping distance in wet conditions. It is important to learn from these countries also as directed and targeted approach can play a key role in solving pressing problems.

*India's nanotechnology initiatives*

In India nanotechnology as a distinct area of government research support started in 2001 with the launch of NSTI (Nanoscience and Technology Initiative) in the tenth plan period (2001-2006) with an allocation of rupees 60 crores (approx. USD 12 million). This programme was articulated and implemented by the Department of Science and Technology (DST), Government of India. In international comparison this amount was insignificant but on the other hand it signaled Indian government commitment to this new emerging field. This programme helped in creating basic infrastructure in the country to undertake nanotechnology research. Department of Information Technology (DIT) also started dedicated programs in nanoelectronics during this plan period.

In the eleventh plan period (2007-2012) more ambitious programmes and targets have been set. Among the major step taken was the launching of 'Nano Mission', follow up of the NSTI programme. It has been allocated Rs 1000 crores (250 million USD), accounting for 36% of the budget allotment in mission mode programs in the eleventh plan period. This programme has strengthened the activities undertaken in NSTI and also new initiatives have been started to develop the nanotechnology research and innovation ecosystem. Among the new initiatives include benchmarking and supporting degree programs in nanotechnology, creating centers of excellence, facilities for access to sophisticated instruments, international collaborative programs, and fostering public-private partnerships. DIT has also undertaken more large-scale programs to develop the nanoelectronics community — centers of excellence in nanoelectronics, INUP programme which provides access to sophisticated instruments, funding and peer support.

The Indian nanotechnology initiative has now evolved as a multi-agency effort with the involvement of other key scientific agencies and stakeholders namely Department of Biotechnology (DBT), Council of Scientific and Industrial Research (CSIR), Ministry of New and Renewable Energy, Ministry of Health and Family Welfare, Indian Council of Agricultural Research, Indian Space Research Organization, Department of Atomic Energy, and Defence Research and Development Organization. Their involvement has helped to strengthen nanotechnology intervention in different sectors, for example DBT (nano-medicine), CSIR (energy, metrology, nano-medicine/pharmaceuticals), ARCI (water, textile, smart materials). Universities have started degree programs and research from their internal funds and some have received extramural research grants. Centers of excellences and nanotechnology centers have been created in some major universities from funding by Nano Mission, DIT and others.

A few companies are also seriously looking at this area. Some of the big companies like Tata, Reliance, and Panacea Biotech have opened dedicated nanotechnology R&D center. Some foreign R&D centers namely General Electric, Intel among others have started user driven research in this field. Industrial associations CII, FICCI, ASSOCHEM are also trying to develop and push government bodies to focus on strategies for industrial involvement in nanotechnology research, regulation and commercialization. Involvement of sector specific associations such as automotive association SIAM is also beginning.

*Nanotechnology capacity creation in India*

The involvement of different stakeholders has led to the creation of capacity particularly research capacity. Centers of excellence have been created in different parts of the country in institutions actively involved in nanotechnology research with the intention of acting as geographical hubs for catalyzing research and innovation. Individual and capacity building projects (procurement of advanced instruments, etc) has helped the research community to develop expertise. International collaborative programs have been initiated with different countries with well directed focus — access to complementary skills, advanced instruments, peer groups, thematic/sectoral programs, etc. Nanotechnology requires interdisciplinary manpower drawing from different fields of science and engineering. Different universities have started dedicated degree courses at graduate level i.e. B.Tech (mainly private university), and post-graduate level (M.Sc/M.Tech). Nanotechnology is now included in the curriculum of graduate/post-graduate level degree programs of science/engineering in many universities or is taken up in post-graduate dissertations. PhD and post-doctoral research are now visible in many institutions. Some efforts are being made to develop benchmarks for course content and uniformity. Model M.Tech course curriculum has been developed by JNCASR. Nano Mission has also evaluated and benchmarked universities imparting nanotechnology courses at post-graduate level. Students and young researchers are also getting access to advanced instruments such as nanofabrication facility available through INUP programme, which is helping in skill development. Some national conferences ICONSAT, Bangalore Nano are having dedicated sessions for students and young researchers to showcase their work and interact with peers.

One can observe now, after a decade of the start of nanotechnology initiative by the government of India, research ecosystem developing in this field with dedicated research groups in universities/research institutes. The capacity is getting more dispersed (nanotechnology research activity is observed in academic centers across the country). Also, it is getting more directional i.e. groups are emerging in key thematic areas.

*Outcome of India's nanotechnology initiative*

Promising leads are emerging from research with novel applications already visible. One of the key features that draw attention is research groups working in developing nano-based applications in areas of pressing concerns namely effective drug delivery, safe drinking water, and energy. Domain specific capabilities are being created; this is particularly visible in nanoelectronics primarily due to the DIT involvement. Similar developments can be observed in the area of water, textiles, energy and health.

The most tangible outcome of India's nanotechnology development is the impressive growth in research papers. India is now the $6^{th}$ most active country publishing in this field based on SCI-expanded database. Significant increase is observed on analyzing the trends over the period (from the start of nanotechnology initiative in the country) in the number of institutes involved in nanotechnology research, in the number of journals used for publishing, more interdisciplinary research (reflection through journals), and activity within different subfields of nanotechnology.

Among the key findings is research collaboration among institutes reflected in papers which is increasing and is instrumental in increasing output, publishing in high impact factor journals and in attracting citations. India is building up on its strength in material science research, applied physics research and physical chemistry while addressing nanotechnology research.

Patenting is in an early stage but show promising signs i.e. they address niche areas of global relevance and in addressing pressing concerns such as in medicine (bio-sensors and drug delivery patents). The areas where India is involved in patent filing and grant activity are 'Nanostructure based therapeutic compounds', 'Chemical process based manufacture of nanostructure', and 'Chemical compound to treat disease'. Most of the patents from India are having biological focus; for example biodegradable polyesters in pharmaceutical compositions, process of immobilizing enzymes, liposomal formulations for oral drug delivery, nutritional supplements to prevent various diseases, bio-sensors. Some other areas where patents are visible include rechargeable batteries, semiconductors, and magnetic nanomaterials.

Indian patenting activity in the US patent office, PCT, European patent office shows it is an insignificant player. Intensive patenting activity is observed in this field in these patenting offices. Patents are undertaken in different stages of the innovation process with dominant activity in nanomaterials (primarily carbon nanotubes), and application of nanostructures. Patents in this field are key instrument in translational/commercialization that has motivated countries active in this field to undertake patenting aggressively. India's low levels of patenting in this field in spite of high levels of research activity are thus a cause for concern.

*From lab to commercialization*

It is too early to say whether India's significant research activity will lead to economic and social outcomes. A few applications are now visible that are showing promising social and economic outcomes. Some of them have emerged from linkages between academia and industry. In spite of low levels of patenting activity, some patents show promising pathways. Thematic groups are visible in some key areas of pressing concerns — water, medicine and energy. Some support structures are emerging to strengthen the sectoral focus and translational research efforts. For example, Nano Mission is now concentrating on establishing thematic units of excellence i.e. directing focus on creating units that focus on nanotechnology as an enabler in key sectors. Nano Applications and Technology Advisory Group constituted under Nano Mission with the objective to encourage implementation of application-driven projects in the area of nanoscience and technology is in this direction. Nano-biotechnology is being supported under DBT's lab to market initiatives under its BIG (Biotechnology Ignition Grant) scheme. CSIR's NIMITLI programme has initiated academia-industry partnership projects in nanotechnology. ISRO, DRDO, etc. are also inviting industry partnership in their nanotechnology research. Tata Chemicals, Reliance, Panacea Biotech are creating their own R&D centers dedicated to nanotechnology research. Some novel applications/products have emerged from these centers.

In spite of some tangible outcomes, there is a long way for 'promising research' leading to applications. Only, a few organisations have been able to translate some of their research to applications. Even many of the applications are in pilot stage and have to scale up before entering the market. Major policy directive with well defined action plan is required for creating the environment (support structures, and functional linkages) that develops/strengthens synergy between academia and industry.

*Nanotechnology Regulation*

Regulation including risk regulation requires very strong push as this is still not properly addressed. Regulation requires accommodating concerns of different sectors where nanotechnology intervention are being undertaken and action plan for addressing them. Moreover, international regulations are evolving such as nanomaterials being defined under chemicals and guided by REACH provision in the European framework. Thus, regulatory framework has to be dynamic and evolve to meet international regulations particularly those visible in major developed countries.

There is no explicit budget allotted for EHS/ELSI and issues covering them are still not in the mainstream discussion and policy articulation. Lack of attention to these issues may adversely impede the development process. Lately some initiatives have been taken for addressing risk issues by Nano Mission and key scientific agencies. NIPER is developing regulatory approval guidelines for nanotechnology based drugs and standards for toxicological tests in nano-based drug delivery systems. In 2010, DST appointed a task force which has been asked to advice Nano Mission Council to develop a regulatory body for nanotechnology in India. Firms involved in nanotechnology based product development primarily products addressing water, textile, drug delivery have undertaken Life Cycle Analysis (LCA) partnering with research institutes/universities. Standardization remains an area of concern. India, has only taken initial first steps in addressing standardization issue.

***Final Remarks and Strategic Priorities***

Extensive investments have been made by different countries in this field with the hope that this will pay-off in terms of economic and social benefits. The 'return to investment' in terms of economic and/or social goal is more pressing for emerging/developing countries as they perceive this technology can help them in the 'catch-up' with the advanced North. Along with this, the potentiality of this technology to address their developmental goals has motivated them to allocate a high proportion of their R&D budget towards this area. This prioritization creates demands for visible outcomes which apply to a large extent for India. The study has examined the efforts undertaken by India to develop capacity for nanotechnology research and innovation in the country and have identified visible outcomes. This assessment shows what has been achieved and the major gaps that need to be addressed. The study argues that properly addressing the gaps can strengthen the present efforts and can lead to responsible nanotechnology development.

Examining dedicated government driven promotion of nanotechnology over a period of more than ten years from its initiation shows some very positive actions have been undertaken. The tangible outcomes particularly the infrastructure created for undertaking nanotechnology research in different domains has been possible because of this government driven intervention. Centers of Excellence have been created in different parts of the country and focused thematic units are being created in the field of water purification, photovoltaic and sensors, medical biotechnology, and automotive application. These centers are playing an important role in developing the research community. Distinct research groups are now emerging in the country. They are now becoming more directed and focusing on sectoral issues/problematic.

There are two kinds of challenges that have to be taken into account and need to be addressed for responsible nanotechnology development in a country. First set of challenges are in the global context of nanotechnology development such as the level of knowledge development globally, regulatory framework in different countries including risk guidelines, standards development, patenting intensity and nature of patenting, patentability examination guidelines, etc. Second set of challenges are country specific and relates to its research and innovation ecosystem in general and aspects covering nanotechnology in particular such as capital intensiveness, sophisticated instruments, interdisciplinary nature of this field that requires specialized human resource generation, academia-industry linkages, translational research capacity, etc.

The study recommends a set of actions that should be undertaken for responsible nanotechnology development in the country. These recommendations are based on this exploratory study i.e.

investigating Indian nanotechnology activity over a period of time and also examining development strategies and outcomes of some advanced and emerging economies in nanotechnology. They are articulated as strategic priorities. The study posits that by addressing them the country's nanotechnology programme will be strengthened i.e. lead to the enhancement of the nanotechnology research and innovation capacity and create suitable mechanisms for research translation; developing novel products/processes that can meet economic and/or social goals, enhance industrial competitiveness.

**Strategic Priority 1**

Nanotechnology in India has evolved as a multi-agency program with involvement of different government agencies providing support for capacity building and sectoral intervention. ***The study recommends creation of an empowered structure that can coordinate investment in research and development (R&D) activities in nanoscience and technology.*** This will create horizontal linkages among different agencies which among others help in coordinated approach to key elements for nanotechnology development such as human resource development, regulation, capacity building, etc.

**Strategic Priority 2**

Developing skilled human resource in this area is challenging as it calls for interdisciplinary competency along with grounding in natural science/engineering. ***The study recommends (a) Creation of interdisciplinary courses and separate program in nanotechnology at post-graduate level that meets the requirement of industry at large (b) Creation of advanced certification/diploma in nanotechnology for imparting students various skills (handling advanced instruments, patenting aspects, etc) and industrial exposure.***

**Strategic Priority 3**

The study shows that well defined mission program and involvement of various scientific agencies has led to the creation of 'research ecosystem'. ***The study recommends that in the next phase it is important to develop a Roadmap/Framework that helps progression from 'research ecosystem' towards an 'innovation ecosystem' and commercialization.***

The roadmap should have a balanced approach: along with strengthening discipline based objectives it should also give emphasis to social needs. It needs to create opportunities for different stakeholders and should have short, medium and long term perspective. For example, short term perspective need to pay attention for exploiting existing knowledge. More focus would be towards development and creating interface mechanisms for scaling up the technology, industry partnership, etc. Medium and particularly long terms perspective would incorporate strategies of short term but also need to place sufficient resources for creation of knowledge, develop governance framework, regulation, etc.

The Roadmap should also give due emphasis for strengthening collaboration/strategic partnerships between academia and industry. Institutional support mechanisms such as Centers of Excellence and Nanotechnology Centers that have been created can act as bridges for developing linkages, creating partnerships in the whole value chain of technology development i.e. from research to innovation and product design. The centers needs to be augmented with different support systems therein such as technology transfer office, patent examination and filing facility, incubation and proof of concept funding, state of art search for assessing current developments, etc. These centers should help in bridging fundamental science and real world applications in different sectors.

Nanotechnology has multiple applications in myriads of sectors. Each sector has its own distinctiveness, inherent dynamism, concerns which needs to be addressed for responsible intervention of nanotechnologies in that sector. Sectoral concerns should be taken into account in the Roadmap.

**Strategic Priority 4**

Nanotechnology development is to a very large extent contingent on access to sophisticated instruments. ***The study recommends dedicated instrumentation program for developing sophisticated instruments.*** The program should be backed by specific policy articulation with long term dedicated funding and with the involvement of academia and industry. This includes developing international collaborations for joint instrumentation development.

For increasing access to sophisticated instruments; existing programs like INUP should be strengthened further by creating more nodal points; access to international facilities such as European Synchrotron Radiation Facility (ESRF), beam lines, etc.

**Strategic Priority 5**

The questions of nanotechnology definition and classification, examination, international rules, etc are key concerns in patenting and standardisation. Institutions engaged in nanotechnology research should have more horizontal linkages with patent office, and standard development institutions. ***The study recommends development of a centre of excellence to examine patenting (patent guidelines in this area, facilitating the patenting process, etc) and other IPR issues, develop linkages between academia and patent office, create joint mechanisms for developing sector specific standards, etc.***

**Strategic Priority 6**

Governance mechanism including regulation and risk mitigation requires urgent attention. ***The study recommends dedicated funding support for EHS/ELSI including creation of a coordinating centre for regulation and risk research.*** The centre needs to address the aforesaid issues in the whole value chain of a product/process development. Regulatory and risk aspects should focus on each sector and take in account the sector specific peculiarities and challenges.

**Strategic Priority 7**

Assessment exercise are very important to gauge the status of the various programs i.e. to what extent they are addressing the objectives; whether the programmes properly address the contemporary and emerging trends, new directions to strengthen the programs, etc. ***The study recommends continuous monitoring and periodic detailed assessment of research and innovation capacity, outcomes and outputs, identify shortcomings and assess new opportunities.***