Learning Lessons from Indian Nanotechnology Development

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Abstract

Huge public investment in nanotechnology in the last decade or so is leading to increasing demand for promising applications. Unlike other emerging technologies, along with advanced OECD countries, emerging and developing economies have devoted their scarce resources for developing scientific and technological competencies in this area with the hope that this investment will lead to promising applications. The present debate on nanotechnology thus has shifted more towards innovation and commercialization issues. Further developing countries are increasingly looking at 'return-to-investment' in terms of nanotechnology intervention in solving developmental problems of water, health, etc. In the present context, the key challenge is in exploiting promising research; developing strategies that provide novel pathways for successful translation. Focus has thus shifted towards the downstream end of the innovation value chain, regulation and governance, issues of patenting and standardization, EHS/ELSI issues (Environment, Health, Safety, and Ethical, Legal, Societal Implication). Research is being pushed to become more directed.

Converting 'blue sky' research into a tradable commodity is a challenge which requires a wide set of competencies and an enabling policy environment among others. What would be the effective policy interventions to bridge the "valley of death" remains a puzzle for policymakers, particularly in emerging economies. The study examines this 'puzzle' in the Indian context i.e. what types of policy interventions can help in exploitation of nanotechnology research for moving up in the innovation value chain that provides competitive technological advantage and on the other hand also able to solve developmental challenges.

Introduction

Nanotechnology is seen as the key transformative technology of the 21st century. Radically novel properties (physical, chemical, biological) that materials demonstrate at the nano-scale[1] promises to revolutionize many industry sectors. Nanotechnology also has potential for addressing some of the most critical development problems in health, energy solutions, agriculture productivity, and water treatment making it an influential candidate for technology choice especially in developing countries. On the other hand it is emerging as a key determinant of technological competency (capability) helping existing industry to become more efficient and competitive; developing novel products and processes that is inhibited by existing knowledge and tools. Stakes are becoming higher as success can provide monopoly to a firm or a country in areas where they can position their nanotechnology enabled products (Tsuzuki, 2016).

Developing competency however, is an immense challenge as it is an emergent science based area where scientific, technological and market uncertainties are high; the disruptive nature of this new technology brings new issues for regulation and governance, among others. Being capital intensive and a highly sophisticated process

[1] size range of 1-100 nanometer; 1 nanometer = 1.0×10^{-9} meter

for creation of state of art infrastructure requires along with high capital, scientific competency and technological skills. The area being highly interdisciplinary calls for capabilities in multiple disciplines. Creating competence would thus require factoring all these issues in the policy and creating institutional structures for implementation.

The Global Push

The National Nanotechnology Initiative launched by the US Government in 2001 as a mission mode multi-agency programme provided a roadmap/vision for development of this area in different sectors with an underlying belief that this technology will create US leadership in different industries (Roco, 2011). This also led to a wider debate on nanotechnology and development i.e. the social implications of this technology. Strongly influenced by the US model, different countries started dedicated programs with liberal public funding support. However, the roadmap of different countries were largely influenced by the expectation from this technology a country had (Bhattacharya et al., 2012). This has to be seen in the larger context of bringing the different influential stakeholders together in pushing investment in a new emerging capital intensive technology of a country. Developing countries for example highlighted the possibility of this technology able to able to solve developmental problems, for instance the possibility of dramatically improving water quality, developing medication for diseases, like tuberculosis and malaria (see for example Salamanca-Buentello et al., 2005).

Some visible outcomes of global investment in nanotechnology can be seen. Huge investment provided the impetus to create advanced instruments for engineering nano-materials. Nanotechnology has emerged among the most active area of research with exponential increase in research papers, patent filing have been very aggressive in influential patent offices, and standard making has led to the joining of different stakeholders with strategic goals (Coccia, 2012). Huge public investment in nanotechnology is leading to increasing demand for promising applications. Some of the "promises" are beginning to take shape with nanotechnology emerging as an enabling technology in improving the functionality of processes and products in various sectors and areas of developmental challenges (UNESCO, 2016, PEN). However, nanotechnology is still a far distance from its perceived promises.

The study examines this 'puzzle' in the Indian context i.e. what types of policy interventions can help in exploitation of nanotechnology research for addressing socio-economic challenges.

Technology Challenges

The market for nanotechnology is primarily restricted to its role in enhancing the functionality of existing products and processes. The nanotechnology market is thus primarily driven by demand for novel nano-materials that can help enhance the functionality of products and processes (European Commission, 2012). Nanomaterials distinguish itself due to its size which gives it novel properties. One of the difficulties in producing nanomaterials in bulk quantity is to retain the nano-size and proper storage. Thus, unlike other technologies, nano-scale provides new challenges that makes the translation from laboratory to commercialization difficult. The production techniques developed in laboratory has to be scalable and industrially viable.

Capturing the innovation and commercialization activity in nanotechnology is challenging due to diversity of applications across sectors and distributed nature of innovation (Rafols, 2011).

Industrial structure surrounding nanomaterials in particular due to its enabling properties and flexibility of applications tends towards vertical disintegration of firms along the value chain. Successful translational research is an outcome of various strategies, policies, developing institutional mechanisms, and support for scaling research from laboratory to a commercial stage, creating linkages between academia-industry-market among others. Science-based technologies are driving innovation in the 21st century. Research in these emerging fields have become more strategic with funding directed towards research that can address industrial problems and technological uncertainties and can lead to more novel products and processes. Industrial research and industry sponsored research to academia sometimes exceeds public funding in these emerging fields. This type of research environment is visible in advanced Organisation for Economic Co-operation and Development (OECD) countries and leads to active academia-industry partnership and startups emerging from academia. Within this context we examine nanotechnology development in India and identify key successful attributes and missing gaps. The study has implications for other countries especially emerging and developing economies as they also confront similar challenges when they enter a new technology where barriers are high but on the other hand there is a promise for leapfrogging the development cycle.

The paper is structured as follows. Section 2 covers literature review, methodology and conceptual framework of the study. Section 3 highlights the salient aspects of nanotechnology development in the country. It draws attention to key attributes that helped in the growth of nanotechnology research and innovation in India. The missing gaps in the nanotechnology development and their implications are discerned. Three case studies were undertaken to further substantiate our findings and discern "how" rather than the "why" of a process (Eisenhardt, 1989; Yin, 2002),. Section 4 of the paper covers the three case studies. Implications of the study are discussed in Section 5.

2. Literature Review

Evidence based policy studies provide rationale for developing polices and mechanisms for strengthening research and innovation ecosystem, creating strategic roadmap and new business models for bridging the gap between laboratory and market. Recent studies show that large firms are driving nanotechnology innovation unlike biotechnology wherein dedicated biotechnology firms emerging primarily from universities drive the innovation process (Genet, 2012). Capital intensive nature of this field, large and diverse knowledge bases that exists in large firms which is a pre-requisite for technology development in this field are cited as some of the plausible reasons behind the influential role played by big firms in driving nanotechnology innovation. Another influential study (OECD, 2010) show that the combined R&D investments in nanotechnology by industry (primarily due to big firm's involvement) has exceeded public investment in many advanced OECD countries. This implies positive market acceptance of nanotechnology as it is demonstrating applications that if further exploited can be translated into novel products or can enhance the potentiality of existing products. Also it can be argued that advanced country markets are more receptive to nanotechnology based applications which is driving industry investment. This trend not observed in emerging economies mirrors the general trend in these countries of industry reluctance in investing in research and innovation. However, venture capital investment globally is still only a small fraction of overall investment plausibly implying that the value proposition that can be exploited is still uncertain (OECD, 2010). Industrial structure surrounding nanomaterials in particular due to its enabling properties and flexibility of applications tends towards vertical disintegration of firms along the value chain (Rafols et. al. 2011). Another area that is an emerging challenge in nanotechnology commercialization is the compliance with evolving stringent regulatory platforms addressing environmental and health concerns, and in the market place overseeing possible anticompetitive practices (Ganguli, 2013).

Distinguishing the issues that emerge from influential studies on nanotechnology innovation and commercialization provides a useful lens for understanding the trends and design effective policy mechanisms. Nanotechnology also follows the typical characteristics of emerging science based technologies. As Ganguli (2013) and others have shown, science based technologies disrupts the traditional models of R&D and technology transfer. Among others, co-production of upstream knowledge, concurrent transfer between industry and knowledge producing entities, development of consortia promoting pre-competitive collaboration drive innovation in emerging technologies (See for example Huggins & Izushi, H., 2007). Absorptive capacity is important for firms to adapt knowledge from public funded institutions (Cohen & Levinthal, 1990). Entrepreneurial activity tends to cluster in regions with experience in related sciences, in top-level universities or research institutes, or with R&D laboratories of major companies (Walsh and Kirchoff. 2002). Venture capital investment is important to bring in know-how and networks and helps in communicating value proposition of applications to potential customers. Patenting is generally very aggressive in emerging technologies and becomes a big barrier for new entrants. Issues of Environment-Health-Safety (EHS)/Ethical-legal-Societal Issues (ELSI) becomes very important due to various types of uncertainties.

Methodology

We have used triangulation method (multimethod research approach) to capture the nanotechnology development in India. This helped us to combine the advantage of both the qualitative and quantitative approach and thus deepening and widening our understanding (Khan and Rahman, 2012). Analysis of research papers and patents in nanotechnology were undertaken by applying bibliometric method to discern the macro trends. This was supplemented by close reading of various policy documents, scholarly articles, newspaper clippings, etc. Interactions with experts, policy makers and industry happened over a period of time to capture the dynamics, inform further the findings and validate the results. Secondly, to have a deeper insight and identify the determinants of success and missing policy gaps, three case studies were undertaken (a) Nano-enabled water filter, (b) Anti-bacterial nano coating in textile, and (C) Bangalore nano cluster. Case studies were based on semi-structured interviews with experts of International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) Hyderabad, IIT-Madras, their industry partners and different stakeholders in Bangalore. The authors' also attended various conferences and events such as Nano India, Bangalore Nano to strengthen the findings of the study.

Indian policy makers had made extensive efforts to locate nanotechnology across key research institutes and universities in the country. This allowed us to have a closer look at the nanotechnology development in the country by focusing on competencies that have been developed across various locations. Bangalore has emerged as one of the most promising centre for nanotechnology research and innovation. What were the key factors that led to nanotechnology development in Bangalore was the main motive behind this examination. Vinck and Ramani (2014) identified key factors that contributed to the development of Granoble nanotechnology cluster. Their study supports the major drivers that Fiore, *et al.* (2011) highlighted for emergence and prosperity of regional innovation system namely the presence of high-tech industries potentially oriented towards international markets, relationships between firms and university system, a specialized labour market and labour force with readily available highly skilled human capital, local traditions of cooperation and entrepreneurial approaches, supporting agencies and organisations, presence of social capital; shared norms, values and trust which facilitate relationships and mutual understanding and learnings; and financial capacity. This study closely followed the above two influential studies in identifying key factors for nanotechnology development in Bangalore.

The larger objective of the three case studies was to further inform the development of nanotechnology research in India.

Conceptual Framework of the Study

The study applies National System of Innovation (NSI) approach to investigate the Indian nanotechnology capabilities and strategies. The NSI approach is embedded within the Innovation System (IS) approach. The core elements of IS approach is that (a) national systems differ in terms of specialization in production, trade and knowledge (Archibugi and Pianta 1992, Nelson 1993), (b) elements of knowledge important for innovation performance are localized and not easily moved from one place to another, (c) the importance of interactions and relationships; relationships seen as carriers of knowledge and interactions as processes where new knowledge is produced and learnt (Dosi 1999, Lundvall, 1992) (d) Learning a socially embedded process governed by the institutional context. NSI can simply be seen as applying IS approach when it is territorially bounded within the national system (see for example Verblane & Tamm, 2012).

NSI presents a useful analytical framework to push the debate on 'catch-up' forward. NSI accommodates the catch-up thesis (Gerschenkron, 1962) that technology catching-up cannot be taken for granted because a variety of necessary and complementary capabilities may be needed for effective absorption of existing technological knowledge, even if freely available. Further the notion of technology gap as argued by evolutionary economist (see for example Verspagen, 1992), provides a useful hyphenation to catch-up theory and has influenced the NSI thesis. The technology gap hypothesis argues that if the technology gap is too large, it is difficult to absorb technology, as the conditions in the countries of origin and the countries of destination are too large.

'Catching up' in this framework also corresponds to the thesis of Altenburg et al. (2008) who underscore catching up not in terms of accumulation of production capabilities but the transition from production to innovation capabilities. Production capabilities they argue can be done by using and adapting existing knowledge; however innovation capabilities implies ability to create new knowledge and putting it to productive use. They do recognize that using it more generally is problematic as innovation often involves knowledge adaption. Borrowing from Bell (1984) and citing empirical evidence of extensive improvement in production capabilities in many countries, they argue that there is no continuum between the accumulations of production and innovation capabilities.

NSI assumes that the commercialisation of innovations in any country in a new science-based sector is a collective process embedded within a system specific to the country. In other words, the creation, development, adoption, and diffusion of innovations evolve as a function of the existence and functioning of networks between the state and a variety of organisations, such as firms, consumers, public laboratories, universities, financial institutions, and civic associations. This framework calls for creation of institutions that promote interactions and learning between divergent actors (government, firm, academia), and help develop capabilities and interventions that can disrupt path dependency (the inertia in the system that inhibits introduction of new technologies).

Drawing from different theoretical and conceptual frameworks, one observes divergent views on public sector intervention and the extent of intervention to support innovation/innovation process (Laranja, 2007). One can observe that different viewpoints converge primarily on two concepts: market and system failure. Market failure is primarily linked to the under provision of public good because of uncertainties, externalities, inability to appropriate the positive externalities of knowledge/innovation, inability to invest because of lack of private sector interest, and missing markets. The system failure concept has emerged from IS approach which posits that markets are not the only actors in a country's economic development. This approach calls for addressing broader set of failures (system failure) that has to be taken into account for public intervention, as there are other actors besides markets surrounding the innovating and economically active firms (Varblane & Tamm, 2012). Scholars such as Woolthius *et al.* (2005), Rondé and Hussler (2005) provide explicit delineation of factors that leads to system failures;

factors they underscore are infrastructure, institutional, network, learning and capability and lock-in failure. IS system framework provides a constructive approach to accommodate and enrich other influential thesis. Developing regional capacity for strengthening national innovation capacity has emerged as an important thesis in the innovation process. The thesis argues that region is the most appropriate scale at which to sustain innovation based learning economy as proximity creates network and social capital among others. Coming from business school perspective, Porter cluster theory (1990) has attracted in particular business management scholars and policy maker's attention to the importance of clusters and its influence on regional competitiveness.

AnnaLee Saxenian (1994) has contributed to further understanding of innovation and competitiveness by highlighting the importance of region and knowledge clusters within region as an important determinant of innovation. Empirical studies have provided support to the above thesis, see for example Huggins and Izushi (2007) has shown that economic growth is strongly associated with regional competency. Their study based on 113 leading economic regions across the globe also highlights the knowledge intensive regions and clusters within them are leading in terms of creating wealth and new opportunities.

Findings

3. Some Salient Aspects of Nanotechnology Development in India

We identify strong Indian government support for promotion of nanotechnology. The role of eminent scientists who could successfully articulate to the highest policy making body the need to invest in this technology was a key determinant for taking a positive stance for promoting this field (Beumer and Bhattacharya, 2013). Two main government actors have been the Department of Science and Technology, and Department of Electronics and Information Technology (DietY). DST articulated the Nano Science and Technology Initiative (NSTI) mission as early as 2001 with a corpus fund of Rs 600 million (equivalent to $15 million). This was followed up with a five year mission from 2007, the Nano Mission with over US $250 million support. was The main objective of DST policy framework was to create a strong scientific environment and enabling infrastructure for nanotechnology research and innovation in the country. DietY played a major role in creating an enabling environment for developing competency in nano-electronics. All major scientific organisations, big industries across different sectors, industry bodies and some state governments showed active involvement.

We observe that the support for nanotechnology is visible in the contemporary times inspite of many changes in the policy environment with the new government. However, the planned support for activity for a five year period has been discontinued with government bringing in a new framework that calls for three, seven and fifteen years programmes. These programmes are strongly connected with deliverables that can be properly measured. The implications for this in nanotechnology at this stage can only be postulated that there will be strong push for exploiting nanotechnology research for achieving desired socio-economic goals.

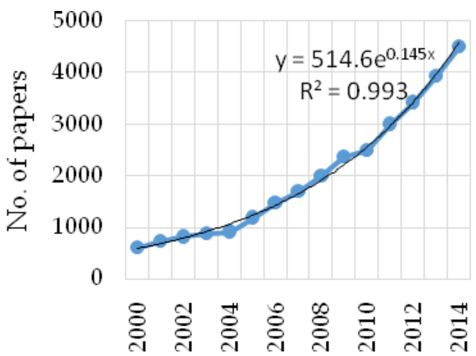
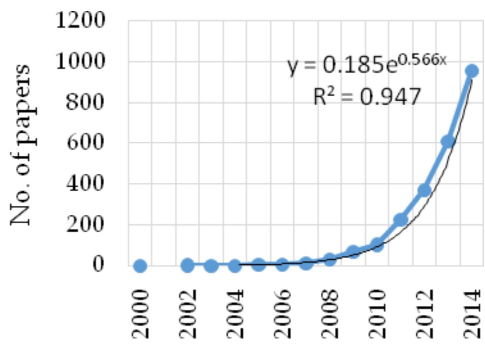
The effect of enabling support system to nanotechnology so far has resulted in developing infrastructure and creating active research groups across different institutes in the country. Varied linkages have been developed across the research and innovation value chain with some regions like Bangalore, Hyderabad, Delhi and adjoining regions (national capital region, NCR), Bombay, Kolkatta and Madras emerging as promising nano hubs. These places have high locational advantage: presence of reputed academic institutions, skilled manpower, global linkages, foreign R&D centers. These places have also benefitted by attracting a large share of funding from government programmes. These locations are also active ICT centers and show good presence of other knowledge intensive firms such as in biotechnology, specialised chemicals.

Importance of Institutions

The study identifies two key initiatives by the Indian government that have led to development of nanotechnology in the country: Creating Centers of Excellence (COEs) in research institutes/universities and Indian Nano Electronics User Program (INUP). COEs have been primarily created through mission mode programmes (NSTI and Nano Mission) and have helped to create dedicated infrastructure and competency in different domains within nanotechnology. INUP programme created by Department of Electronics and Information Technology (DietY) is helping to develop the nano-electronics ecosystem. INUP provides access to sophisticated instruments and peer supports to groups involved in nano-electronics particularly to universities. It has also developed a few COEs.

One measurable outcome acting as a proxy indicator of research competency is research publications. India shows a strong presence in this indicator; it is now ranked 4th in research publications. Particularly promising is India's research activity in novel nanomaterials namely carbon nanotube and graphene (Figure 1). These two materials have shown new possibilities in developing nano-based products and enhanced enabling properties.

Figure 1: Indian Publication Trends in Carbon based Nanomaterials

<table>
<tr><th>Publication Trends in Carbon Nanotube</th><th>Publication Trends in Graphene</th></tr>
<tr><td>
</td><td>
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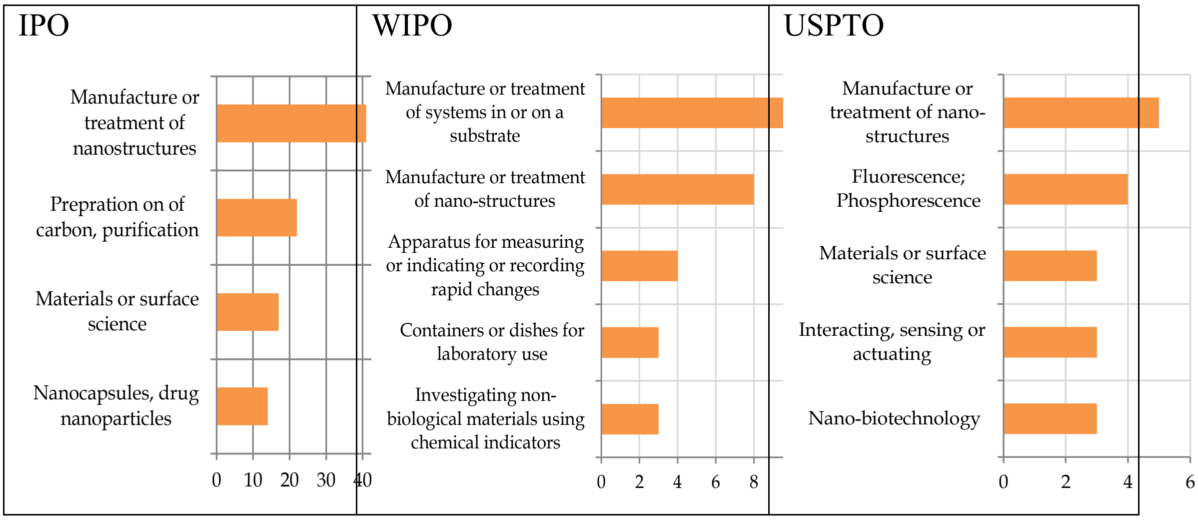
Indian Patenting trends do not match with research trends, however, it is promising to observe strong connect with patenting happening in areas of developmental concerns. Indian assignees filed 50 patents in US Patent Office (USPTO), 57 through PCT (WIPO) and 117 patents in Indian Patent Office (IPO) from year 2001-2014. Figure 2 gives further details of the International Patent Classification (IPC) classes[2] where Indian Assignees have filed patents in the three patent offices. Treatment and manufacture of nanostructures is the dominating area of application in all the three patent offices. Preparation of carbon-based nanomaterials is also a dominating class in IPO. Another dominating class is materials and surface sciences in IPO and WIPO. Investigation of biological and non-biological material using chemical indicators or fluorescence is also dominating in WIPO and USPTO. Some other visible classes are nano-biotechnology, drug delivery and sensing systems.

Figure 2: Prolific IPC Classes of Indian Patents Filing in Three Patent Offices



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

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

An estimated 300 firms show involvement in nanotechnology that includes Indian as well as foreign multinationals (CKMNT). 300 firms include approximately 100 foreign firms (Figure 3)

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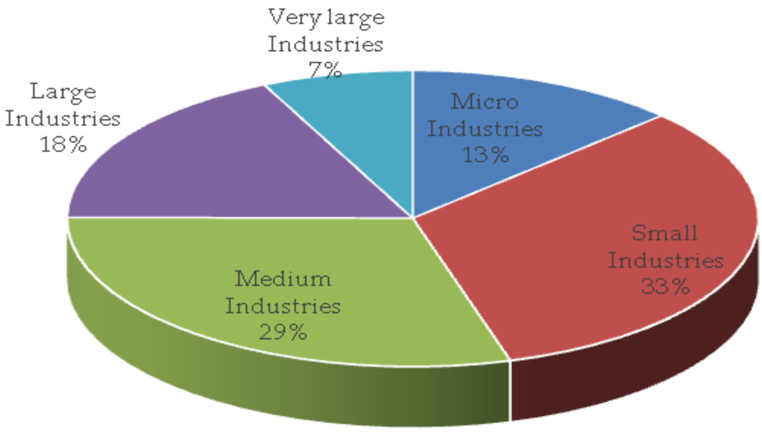
[2]International Patent Classification (IPC) provides a hierarchical system of symbols for the classification of patents according to the different areas of technology to which they pertain.

Figure 3: Nanotechnology Firms in India



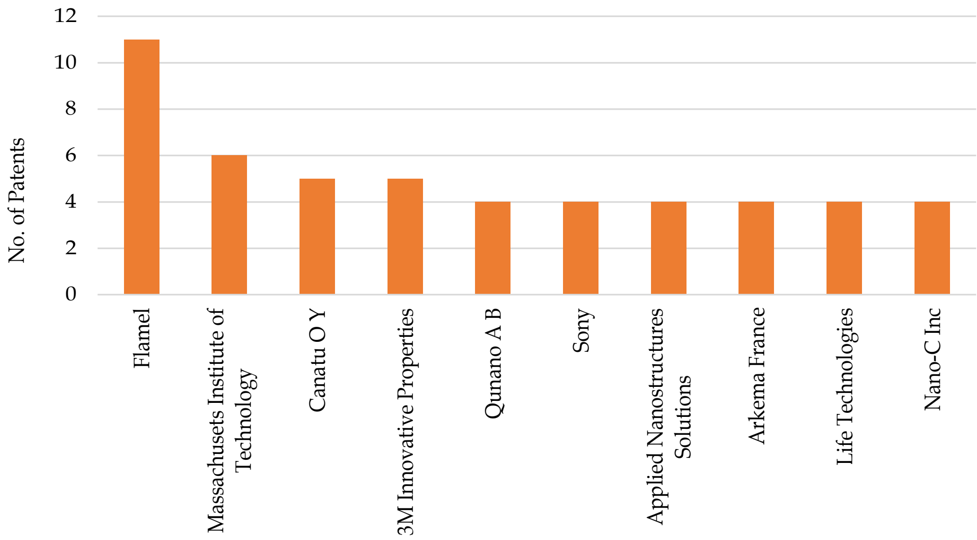
Source: Author construction from India Nanotechnology Industry Directory by CKMNT. Size wise break up was done on the basis of number of employees in a firm; Micro (less than 10), Small (11-100); Medium (101-1000), Large (1001-10000), Very Large (above 10000)

A wide dispersion is seen in terms of size and operation domain and geographical location. Majority of nanotechnology firms are located in Mumbai, Pune, Bangalore, Hyderabad, Ahmadabad, NCR and Kolkata. The presence of excellent universities and research centers seems to be a plausible driving factor for location of nanotechnology firms. This is unsurprising as this is a science based research area. Micro and small firms are primarily involved in bulk production of nanomaterials while large and medium firms are exploring nanotechnology intervention in their established products. Almost all major pharmaceutical firms are active in exploring nanotechnology for drug delivery systems. Similarly all major paint companies are exploring nanomaterials applications to make efficient coatings. A few textile firms are exploring nanotechnology for enabling properties of wrinkle-free, anti-bacterial fabrics, having good elasticity and strength. One can also observe major textile Industry association ATIRA involvement in developing nano-fiber textile.

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

Involvement of Indian firms in patent filing is significantly low. On the other hand foreign firm’s involvement in IPO is much higher. Around 200 foreign entities and 35 Indian entities have filed patents in IPO in nanotechnology. Figure 4 highlights the foreign entities actively involved in patent filing in IPO. Dispersion of foreign filers in terms of their location and activity areas can be observed: France based pharmaceutical company ‘Flamel Technologies’ followed by ‘Massachusetts Institute of Technology’ in USA, ‘Canatu O Y’ a Finland based company operating in the area of Electronics devices and gadgets, ‘3M Innovative Properties Company’ from USA a service provider in the area of intellectual property.

Figure 4: Prolific Foreign Entities Filing in India



Source: Thomson Reuters Patent Database

‘Sony Corporation’ from Japan working in the area of electronics, ‘Arkema France’ working in the area of chemicals and advanced materials, and ‘Nano-C Inc’ from Westwood working in the area of carbon based nanostructures, Qunano AB from Sweden working in the area of semiconductor and non-semiconductor nanowire technology with application in diverse fields, ‘Applied nanostructure solutions’ from India is working in production and commercialization of Carbon Nanostructures and ‘Life technologies’ from India working in the area of pharmaceuticals.

Nanotechnology innovation and commercialization to a large extent is dependent on addressing risk. The risks associated with nanotechnology are due to associated ‘uncertainty’. The notion of uncertainty refers to all possible, new, imaginable hazards, with which society has no or limited experience. Uncertainties make it hard to perform quantifiable risk assessment in order to establish a clear threshold value for commercialization. Uncertainty is also about limited knowledge of future product capabilities, process integration capabilities with current manufacturing practices and uncertainty about market. The uncertainty associated with the present knowledge in this domain makes it difficult to craft a regulatory framework that covers all the facets of nanotechnology.

In technology parlance, regulation is typically understood in terms of developing measures for anticipating and mitigating adverse impacts of technology. The debate has now shifted towards developing institutional mechanisms for ‘responsible development’. Regulation for fostering innovation has attracted less attention

(Heldeweg and Kica, 2011). We posit that regulation needs to cover different stages of the innovation process along with addressing risk issues at the upstream as well as downstream end. Regulatory bodies needs to ‘factor in’ this approach while debating on best possible strategy to develop the regulatory framework. Responsible technology development, EHS/ELSI aspects have not found any specific mention in the nanotechnology policy articulations in India. However, Nanomission has funded a few projects in this area. Recently, some initiatives have been taken for addressing risk issues by some institutions. ARCI has commissioned a study on impacts of its product nanosilver based water filter on environment, issues of recycling, and life cycle analysis. Indian Institute of Toxicology Research is investigating the risks of nanotechnology partly through funding of DST and European Framework Program. Another group at CSIR-Indian Institute of Toxicological Research (CSIR-ITRC), is also working in toxicity studies. National Institute of Pharmaceutical Education and Research (NIPER) is developing regulatory approval guidelines for nanotechnology based drugs and standards for toxicological tests in nano-based drug delivery systems. Problems with addressing EHS issues in India can also be attributed at some level to the fact that these aspects- environmental health, community health and occupational health are all distributed across different ministries. There is no institutional mechanism for coordination. ELSI issues also requires more intense activity. It is restricted to only a few institutes in India. In 2010 government announced the establishment of regulatory board for nanotechnology. It is important that institutionalisation of this board takes shape.

Standardization activity remains an area of concern. Standards have emerged as a strategic tool in emerging technologies as bodies promoted by national governments are developing anticipatory standards i.e. standards developed ahead of the technology. Standards thus are acting as change agents, guide to the market and providing decisive advantage to countries/firms which are able to successfully develop and push the standards globally. This has happened in ICT and is seen emerging in nanotechnology. Along with a few OCED countries, we find China and South Korea actively involved in this type of exercise with their policy roadmaps and implementable strategies strongly reflecting this aspect. India has not flagged this in their policy roadmap and acting more as a follower country in implementing standards which are now developed in this field.

4. Case studies were undertaken to have a more informed assessment of nanotechnology development and identify some important parameters that can be missed when examination is done at a macro level.

Case Study 1: *Development of Water Filter*

We have examined two organisations involved in development of nano-enabled water filter (a) International Advanced Research Centre for Powder Metallurgy & New Materials (ARCI) at Hyderbad and (b) Dr. Pradeep and his group at IIT-Madras.

Dr Pradeep and his group had a long term strategy for development of water filter and their whole research group centered on development of efficient and economically viable water filtration technology by exploiting nanotechnology. Progressive effort was made which resulted in incubating a startup ‘InnoNano Research’ at IIT-Madras Research. The nano-filtration technology developed was successfully transferred to a well-established brand in water filters namely Euraka Forbes. This startup later became a private limited company and opened a new research lab at IIT-Madras Research Park. InnoNano research also addressed the water contamination issue in rural areas in regions particularly effected by arsenic and other contaminations. Water filter ‘AMRIT’ developed by them have been installed in 750 locations across the country and provides safe drinking water at less than 5 paisa per litre to nearly 500,000 people. The unique attribute of this product is that it functions without electricity or running water.

On the other hand water filter developed by ARCI also demonstrated its efficacy in removing bacterial contamination. This technology was transferred to a firm M/S Aqatech Pvt Limited. The firm developed a production plant with 1000 liters per day capacity. The product was marketed under the brand name ‘PURITECH’. However, the firm realized that this process was not economically viable and support system that was continuously required for further development of this technology was not available.

Case Study 2: Anti-bacterial Nano Coating in Textile

Manufacturing order free anti-bacterial textiles by using nano silver suspension has been one of the promising areas of nanotechnology intervention. These types of textiles have created niche market for medical establishment, innerwear, sportswear, baby care product and general wear. ARCI took an early lead by developing highly stable nano silver suspensions that can create smart textiles. ARCI successfully synthesize nano silver suspension having particle size of 20-50 nm. In the early stages itself it interacted with M/S Resil Chemical Private Limited, a Bangalore based company that supply chemical finishes to its textile industry clients. The firm willingness to interact and develop the technology further in terms of industrial scaling and consumer requirement was based on its assessment of market opportunity. The interaction helped ARCI to up-scale its production process of nano silver suspensions from 100ml batch to 15 litres per batch.

Interaction with the firm also helped ARCI to optimize various process parameters for obtaining consistent quality and physico- chemical properties of the nano suspension. It also helped in making the suspension stable after dilution and proper storage (a technology challenge as nano suspensions are highly reactive and can quickly loose the properties) of the suspension. This technology was commercialized by Resil and they produced nano silver suspensions in batch size of about 60,000 Kgs. The product development and successful commercialization happened due to the strong public private partnership, a key lesson which this case study highlights. Further interaction by the authors with this firm drew attention to the problems the firm phased in entering the European market due to regulatory requirements. Herein, it shows the need for government providing support to firms for addressing regulatory requirements of different markets especially European market, US, etc.

Case Study 3: Emergence of Bangalore as a Nanotechnology Hub

Bangalore city has evolved over a long period to emerge as a dynamic knowledge city with reputed universities, research laboratories, large public sector firms, and a hub of ICT and Biotechnology firms. Origin of majority of Indian ICT and biotechnology firms can be traced to this city. In the last decade or so almost all major transnational corporations in ICT and also in other areas such as aerospace, biotechnology have opened their R&D centers in Bangalore. Krishna *et al.* (2012) highlight how R&D centers of transnational corporations has developed extensive linkages with IISc and other institutes in this city. Indian Institute of Science (IISc) and University Visvesvaraya College of Engineering were established as early as 1909 and 1917 respectively and a number of public sector undertakings and laboratories were established after India’s independence in 1947 primarily in machinery, electronics, aerospace, etc. However, the transition of this city as a place where knowledge can be exploited to create wealth started from 1980s with Texas Instrument opening its R&D centre in this city, and emergence of two Indian ICT majors Infosys and Wipro and later biotechnology firm Biocon from this place. As recent study by Balasubhramanya (2017) show, Bangalore is emerging as global tech startup hub, and is now home to the third largest startup in the world. Based on empirical research, the study highlighted various enabling factors that has contributed to the development of an entrepreneurial ecosystem. The author also draw attention to the good weather the city has which is an important enabling factor.

Study of nanotechnology activity in Bangalore was examined within this context. A close examination of Bangalore shows its high appetite for Future & Emerging Technologies (FET). Nanotechnology adoption by the research community of this city with enthusiasm can be seen in this light. In fact leading Indian scientist Prof C.N.R who belongs to this city was a key motivator behind government articulation of NSTI and Nano Mission. He has also been associated in various capacities with two key institutions namely IISc and Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) that provides a strong impetuous for nanotechnology development in the country. He has been Director of IISc for a long period and helped establish JNCASR in 1989.

A more informed view of emergence of Bangalore as a nanotechnology hub is visible by examining the firm level activity. Presence of big multinationals and startups in the area of IT, biotechnology and pharmaceuticals make Bangalore a key region for nanotechnology enabling in different products. These firms are exploiting nanotechnology research to provide advanced functionality to their products. One of the important evidence of this is visible from the increasing activities of big ICT and Biotechnology firms like IBM, Wipro, Biocon and Bioplus. These firms are exploiting the linkages they have developed with academic institutions to push nanotechnology based innovation forward.

IISc has been active in providing incubation support to the faculties and researchers for translating their promising research. Two startups have emerged from CenSe, IISc Bangalore: i2N Technology, and Pathshodh healthcare supported by Society for Innovation and Development (this society constituted by faculty of IISc). Another startup from IISc Bangalore is Pendorum technologies supported by BIRAC. BIRAC (Biotechnology Industry Research Assistance Council) is a ''not-for-profit company' of government of India and is providing early stage funding support.

One indication from the primary survey was that finance is a major issue for startups to establish themselves. Many researchers felt that few mechanisms are available from the government departments for providing funds for taking products from pilot stage to market. The motivation of scientists/professors emerged as the most important factor for building the start-up environment. Motivation and support provided by IISc faculty to young researchers for exploiting their research to create novel products, incubate etc was cited highly as a driving factor. There is concern about EHS/ELSI issues, to develop processes that are not toxic. Another aspect that emerged was the strong urge to develop nano-based solutions that can create socially valuable goods

Table 1 highlights some of the active nanotechnology firms in Bangalore. Overall we could identify around 40 firms or so involved directly in nanotechnology or are exploring possibility in nanotechnology based interventions. There were number of small firms (17 in number) with less than 30 employees and are working in the area cross cutting (6), health and fitness (5), electronics and computers (3), energy (1), appliances (1). In some of the firms such as Cranes Software, we see active involvement of faculty from IISc.

Table 1: Some Bangalore based Nanotechnology Firms

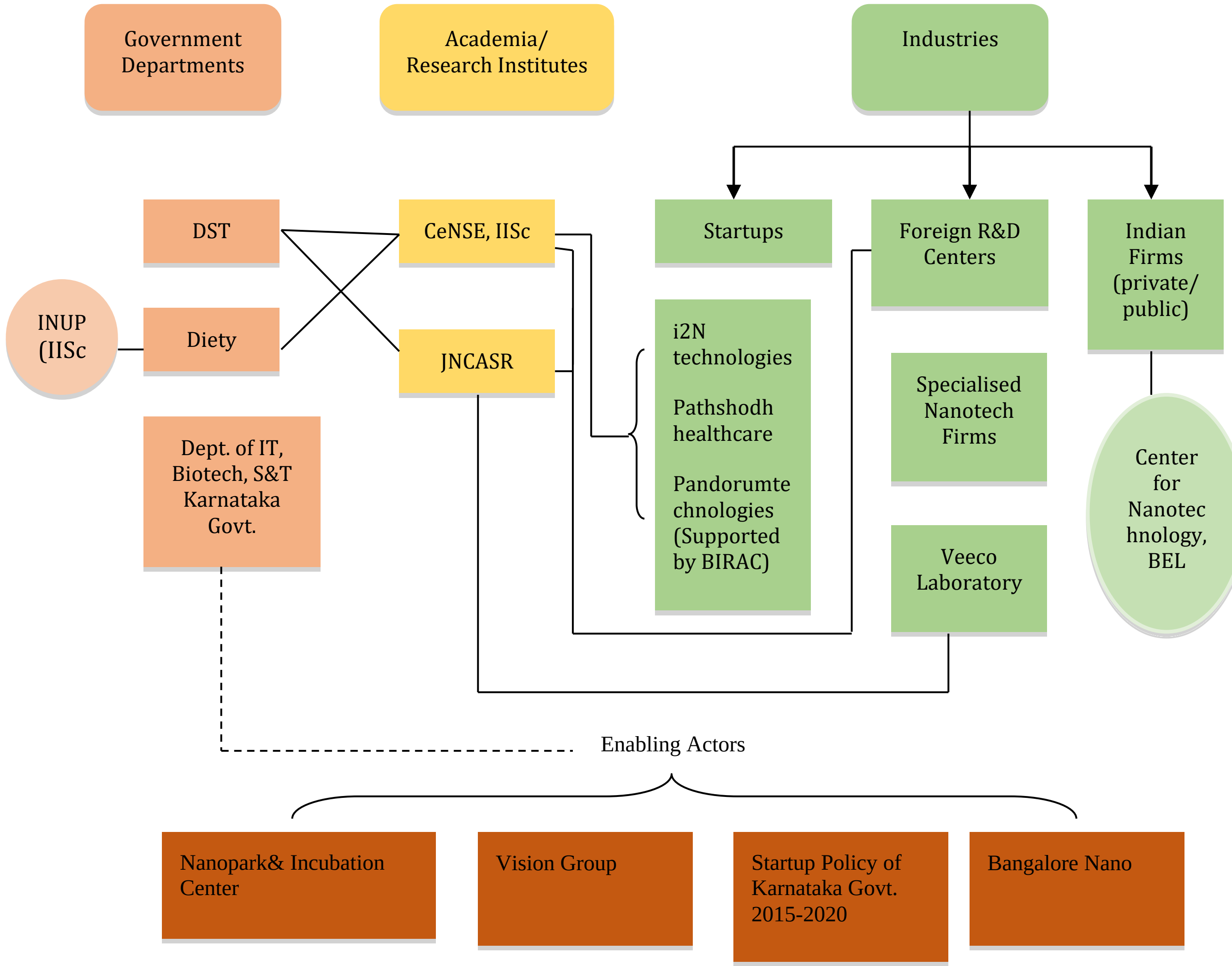
Name of the Firms	**Specific Areas**
Quantum Corporation	Nanomaterials and Nanocomposites
United Nanotech Innovations Pvt Ltd.	Graphenes and nanocomposites.
Velbionanotech	Nanobiotechnology and nanomedicine
NoPo Nanotechnologies India Pvt Ltd.	Carbon nanotube
NANOTECH INDIA	Specializes in offering enterprise solutions, support and services
Vi Nanotech Pvt Ltd.	Supplier, trader and distributor of surface coating products at nano scale
Cranes Software International Ltd	Electronic component at micro and nano scales.
NanoBio Chemicals India Pvt Ltd.	Nanoparticles- peptides and biochemicals.
Bharat Electronics Ltd.	LCD manufacturing activity. Enabling nanotechnology for functional enhancement

Qtech Nanosystems Pvt Ltd.	Focused on making products based on nanotechnology in diverse areas.
GE India Technology Centre	It has a large technology centre in Bangalore. Main focus in nanotechnology is in nano alloy
Veeco Instruments Inc.	A leading supplier of instrumentation to the nanoscience community. This firm has opened a instrumentation centre at JNCASR for joint development of nano instruments
Bharat Heavy Electricals Ltd.	Power systems and products. Strong linkages with IISc, IIT-Madras, IIT-Bombay in nanotechnology

Source: Constructed from various sources

We could discern some key aspects that has led to the development of nanotechnology in Bangalore. This was based on interactions we had with faculty of IISc, JNCASR, and with experts and industry during Bangalore Nano events. This was supplemented through secondary study of research papers, reports, govt. policy documents and newspaper clippings. Figure 5 is a stylized version of the different actors involved in making Bangalore an emerging nanotechnology hub.

Figure 5: Stylised Version of Actors Involvement in Developing Nanotechnology in Bangalore



We can discern two key factors that we argue has helped in making Bangalore a happening place in nanotechnology from the stylized figure.

Development of Key Institutions

(a) The Centre for Nano and Soft Matter Sciences (CeNS): The Centre for Nano and Soft Matter Sciences (CeNS) is an autonomous research institute under DST, Government of India located in Bharat Electronics Limited (BEL) campus, Bengaluru. DST provides core support to the Centre in the form of a grant-in-aid for conducting basic and applied in nano sciences. It is being mentored by Nano-Mission of the Government of India. The research activities in the Centre are: developing nanomaterials through novel synthetic methods, manipulation and control of material properties and translating them to potential products by up-scaling and prototyping. Its establishment inside a major public sector undertaking has helped this centre to develop linkages with industries such as Tata Steel, Hindustan Petroleum.

(b) Indian Nanoelectronics User's Programme (INUP) at IISc: This centre has been providing opportunities to researchers and industry to further develop their expertise by using the advanced instrumentation facilities and discussing their technological problems with experts. Providing research grant, training workshops, supporting application oriented projects in nano-electronics with the objective of developing skilled manpower and products.

(c) Centre for Nano Science and Engineering (CeNSE, IISc): The centre is actively involved in nurturing inventors who are interested to start high-tech ventures in nanotechnology. The center provides a research oriented environment and hi-tech facilities and technical expertise of scholars in IISc. In this direction Society for Innovation and Development (SID) was founded in 1991, in close collaboration with the IISc. SID is registered under the Karnataka Societies Act. This society helps the innovators in various ways that can lead to creation of successful startup.Two nanotechnology startups have been incubated through SID.

Enabling factors for nanotechnology development in Bangalore

One can observe a proactive role being played by different actors to create a nanotechnology research and innovation ecosystem with a strong focus on startup and entrepreneurship. Some of the important initiatives are:

(a) Establishment of Vision Group on Nanotechnology—Founded by Prof C.N.Rao, this group consist of 14 members comprising of nanotechnology experts, industry representative, and representatives from state govt. The group plays an advisory role to government and provide suggestions such as policy initiatives to be taken by the state government for propagating the application and uses of nanotechnology in various walks of life; measures to be adopted for generating increased interest in nano-sciences and nanotechnology among the academia and student community; spreading awareness about nanotechnology and its usefulness among the general public; promoting and incentivising industrial applications of nanotechnology; roadmap for structure and constitution of the proposed national nanopark/nano-centre at Bangalore; organising and structuring of Bangalore Nano event every year and any other subject relating to nano-science and nanotechnology which government may refer.

(b) Development of a nanotechnology roadmap with involvement of Karnataka Government and Vision group. This roadmap is a vision document for making Bangalore a global nanotechnology hub. The roadmap also provides directions for reaching the envisaged vision.

(C) Establishing a Nano park and Incubation Center in Bangalore on a public-private partnership (PPP) model to give encouragement for the young and talented entrepreneurs to start-up their ventures in this emerging technology. Towards this an amount of one billion (Rs. 100 crores) has been committed by the Karnataka governments and the state had provided 14 acres of land. The park is promoted as a national incubator of nano science research, as a hub for startup and entrepreneurship. The Nano Park in Bangalore articulates the following schemes and activities: Nano Incubation Centre (NIC*):*About 50,000 sq. ft. area for housing a variety of analytical instruments and technological tools with clean and semi-clean rooms.Science and Technology Based Business Incubator: Incubate early stage entrepreneurial ventures based on Nanoscience & Nanotechnology innovation. *Facilities and Services:* Physical infrastructure and support systems necessary for business incubation centre. *Nanotechnology Industrial Cluster*: Core infrastructure with world-class facilities for establishment of industries for commercial ventures.

(c) The Karnataka Start-up Policy 2015-2020 aims at stimulating growth of start-ups in manufacturing IT, BT and Nanotechnology. It plans to unite all the available benefits under different policy schemes of the State, and make them available to start-ups. Aims to open many incubators across the state, through a public private partnership, and foster entrepreneurship in colleges. Specifically the objectives of the policy are to create a world class start-up hub, new age incubation network to promote innovation from young scholars, encourage research and development, provide funding at idea stage, providing infrastructures by public-private funding's, support innovations which have potential to address social challenges.

(d) Organising an annual event Bangalore INDIA NANO by Karnataka Govt. in partnership with Vision Group on Nanotechnology and JNCASR. This event provides a platform for academia-industry interactions and also for young scholars and entrepreneurs to interact with peers and industry. It also provides platform to firms and academic entrepreneurs to demonstrate their nano-enabled products.

5. Discussion and Conclusion

Nanotechnology is science based technology and promises to emerge as a key driver for future innovations across different sectors. Scientific and technological uncertainties are immense and downstream end of the innovation value chain is contingent upon addressing the upstream challenges and market uncertainty. New nano-materials for example on one hand exhibit promising possibilities but on the other hand requires extensive efforts for translation as a viable enabling material for enhancing product properties. The challenge has been and will continue to lie in crystallising the "plausible" into affordable "marketable tangibles" for profitable and sustained businesses. This is the acid test of practical commercialization of R&D results. As nanotechnology is entering the downstream and increasingly the market is opening up to nano-enabled enhanced products, the definitions are evolving to address the new changes. New regulatory concerns are also forcing new guidelines to be created with more clarity in the definitions. The evolution of 'nanomaterials' definition itself provides a clue to how policy makers are beginning to address the new concerns as well as delineating product space of nanotechnology.

One of the major arguments of IS approach/conceptual framework is that institutions need to be created and should evolve with the changing environment to address system failure. Institutions help to create linkages with diverse stakeholders and promote learning; a key determinant of a successful innovation ecosystem underscored in this conceptual framework. Learning is seen as a socially embedded process. Translation is characterized by complex non-linear feedback mechanism involving science, technology, learning, production, policy and demand (Edquist, 2006). This framework helps to draw important insights from the findings and provide some suggestions for policy interventions that can contribute towards developing and exploiting nanotechnology research and innovation.

Nanotechnology support in India has been mainly directed to strengthen the supply side of the innovation process following a linear model of innovation. The government push has resulted in developing a strong research ecosystem. On the other hand the policy provides limited support for scalability of R&D, industrial support for risk assessment including life cycle analysis and developing market through fiscal and non-fiscal incentives. The ecosystem does not provide opportunities for interactive learning as linkages among the actors are not sufficiently developed due to lack of institutional mechanisms. As case studies discussed latter shows, it is more of initiatives undertaken by motivated organisations and individuals that are able to disrupt the linear model.

Emergence of Indian firms in this new technology pushes the envelope. The firm composition shows well-established firms exploring nanotechnology in creating new functionalities in their established products. Small and medium firms are in bulk nono-materials. We observe emergence of vertical as well as horizontal value chain. A few good examples of academia-industry linkages leading to successful translation are visible. However, a closer examination shows that majority of the firms are in the lower end of the value chain, producing nano-materials. A few pharmaceutical firms are enabling their incremental innovations (primarily drug delivery platforms) with nanotechnology interventions. This scenario is similar to other domains where nanotechnology interventions is seen i.e. tyre industry, textiles, etc. However, the promises that research is showing in sensors, bio-imaging, energy efficient solutions are not addressed by Indian firms. Patent statistics indicate major gap in innovation capability.

Opportunities and benefit of nanotechnology can only be realized within a clear regulatory framework that fully addresses the very nature of potential safety problems relating to nano-materials. Regulation would also entail looking very closely at standards creation through linkages with international bodies and national ones. Regulation has to be seen in a larger context not confiding itself only to technological risk but as an innovation enabler. Overall when we examine regulation and standard making in India in nanotechnology, we find that in comparison to activity of key stakeholders in nanotechnology globally, India’s activity requires more dedicated efforts without which it will impede India’s efforts to exploit its promising nanotechnology research.

Learning from our empirical study and applying NIS framework leads us to posit some key policy interventions. A new technology has difficulties in competing with established technologies and thus it is important to develop support systems that can be enabler for linking to the innovation value chain. Research and development at the nanoscale requires a large degree of integration, from convergence of research disciplines in new fields of enquiry to new linkages between start-ups, regional actors and research facilities. Technology platforms development, their construction and implementation are increasingly recognized as important in enabling innovation, as a key part of business models of (high-tech) start-ups (Robinson et al. 2012).

The above findings calls for innovative policy interventions, not restricted to linear view of funding as largely the case in India. Indian firms in general have path dependency and low capability and thus cannot exploit opportunities a new technology like nanotechnology can provide. Thus, nanotechnology policy intervention has to support the different stages of the innovation process and has to provide incentives for knowledge creation and exploitation, entrepreneurship and market formation. Compared to Western Europe and the United States, risk issues were not debated in India for a long time. Potential risks of nanotechnologies only become an issue of debate by the end of last decade (Beumer and Bhattacharya, 2013). Among the important issue that needs deeper investigation is: How risks and benefits are taken into account? A strong regulatory environment may effect time to market, marginal cost structure and allocation of resources, however; on the other hand it may contribute to consumer and investors confidence in the technology. The conflicts emerging from Genetically Modified food crops in India has primarily been due to limited involvement of diverse stakeholders and transparency in regulatory approval. As promises are beginning to be seen in nanotechnology with a few translations happening, it is important that dedicated research support is given in addressing risk and governance issues. Will a separate agency as argued by Jayanthi *et. al* (2012) for nanotechnology governance would be a right step in this direction? This is an aspect that requires more deliberations. It calls for a new style of governance where engagement has to be much wider and should actively be reflected in policy making, developing implantable strategies and across the innovation value chain. Institutions have to be created and developed that can facilitate networking, learning from each other and create trust.

Standardisation of measurement and test methods for risk assessment of nanomaterials is still a low priority in the Indian nano funding. Nanotechnology funding towards EHS/ELSI, it is still an afterthought in the Indian case. It is estimated that almost 15% of public funding in US is in this domain. European Commission and EU framework programme has taken decisive steps towards creating institutional mechanisms to address this domain (see for example European Commission Second Regulatory Review in Nano-Materials, 2012). On the basis of their various studies and deliberations they have challenged the hypothesis that smaller means more reactive, and thus more toxic. They have called for case-to-case examination for risk assessment of nono-materials. Other scholars like Robinson *et al.* (2012) argues that for innovation to succeed in areas like nanotechnology, actor alignment from the research laboratory to product development and eventual application area is necessary. They posit this alignment is difficult in emerging technologies like nanotechnology where the technology field is not well understood; the actors are not fully known, and where regulation is largely ambiguous due to various un-certainties. The key message thus is to create institutions which can facilitate these types of alignment.

Learning from the Case Studies

The study highlighted many promising nano based technologies that have been developed. However, many of them did not reach the market or could not be successful. It is important to learn from 'successes' as well as 'failures' to address the missing gaps as well as strengthen aspects that contribute to success. The two case studies (a) Enhancing the functioning of water filter through nanotechnology intervention, and (b) Developing anti-bacterial textiles by applying nano silver suspensions, revealed some important insights that have implications for research translation. Further, based on primary and secondary study, the factors that contributed to Bangalore emergence as a major hub of nanotechnology in the country was identified. This focused study provides us to inform further the policy actions that can strengthen nanotechnology development.

Development of Water Filter

Strong social welfare as a motivation for development of water filter was observed in both the institutes ARCI, Hyderabad and Dr Pradeep's group at IIT-Madras. The case study highlights some important attributes that are essential for successful development of a product not typical only limited to nanotechnology. These we discern as follows:

(a) *Locational advantage*. IIT-Madras Research Park has emerged as a successful technology hub with as many as 40 successful startups that have incubated from this park. This park has developed extensive linkages with foreign R&D centers and Indian firms with many IIT Madras faculty acting as important bridges in developing the linkages. They are themselves involved in incubating startups or act as mentors in many cases. Startups are encouraged with liberal support to graduate to a company. This can be seen in this case also. Dr Pradeep's group started a startup company at IIT Madras Incubation Cell in 2008 which graduated as a company InnoNano Research Private limited. InnoNano has a new research lab of around 5000 sq. ft. size at this park. Dr Pradeep and his group thus had a major locational advantage compared to ARCI. Social and network capital play an important role in the innovation process. Social capital is defined by its function; this common function is the creation of localised trust (Coleman, 1988). Network capital consists of value inherent in networks and relationships generated through interactions motivated by business or professional expectations (Huggins and Izushi, 2007, pp. 59) We observe that Dr Pardeep's group has developed these important resources social and network capital. Location of their company inside the research park played a key role in this.

(b) *Creating Business Entity*: Dr Pradeep and his group realized that research competency is not enough to develop a successful product. Their group also believed that core competency requires sustained activity. Their journey from a startup to a private limited firm and developing a portfolio of addressing various quality problems associated with water provides them with a unique advantage. Their ability to successfully scale up as observed from their product ‘AMRIT’ shows not only their technological capability but also demonstrates the business and organizational capacity they have developed. (c) *Attracting Investment/Funding Support*: Both ARCI and Dr Pardeep group had funding from Nano Mission. However, by successfully transferring its technology to Euraka Forbis and also by providing safe water solution to rural areas at low cost and high volume provides Dr Pardeep’s firm with steady revenue. Their main advantage has been their dedicated focus on one area (Water). They are continuously addressing various aspects of the value chain in this area—technology and product development, manufacturing and conducting trails and reaching out to users. Inno Nano Research is now developing all in one water purifier to address a wide spectrum of water contaminants. They have already developed a water filter capable of removing fluoride which is being commercialised. Already they are thinking big to create a new manufacturing facility to supply water filter for the international market. All these have made them attractive to global venture fund firms as can be seen from $18 million funding they have received from Nanoholdings (Connecticut, USA) recently. On the other hand Government has also become an active supporter of their activity. Ministry of Drinking Water and Sanitation has recommended the replication of their water filter in all states where drinking water is contaminated with arsenic.

Dr Pradeep’s group over the years has developed an extensive interactive and learning environment in the technology development, scaling up, enlarging the functionality of their water filter. Learning from market/consumer has been an important contributor to Dr. Pradeep’s group in developing capability. Thus the two cases provide contrasting example of failure and success which was due to one group better understanding the market mechanism and learning from interactions with the firm and other stakeholders. It was also due to their exploiting the locational advantage and continuously involved in developing innovation capabilities. Catch-up thesis in this case is not merely developing production capabilities by knowledge absorption but more in terms of developing innovation capabilities linked to production process.

Anti-bacterial Nano Coating in Textile

The successful transfer of anti-bacterial nano coating in textile by ARCI shows the importance of active interactions of the institute with the firm (Resil Chemicals Pvt. Ltd) to whom the technology was transferred. Scaling up was a big challenge. Storage was another key issue as high reactivity required innovative solutions to tackle this problem. Only by active interactions, the optimization of process parameters to obtain consistent quality, stability, proper storage etc were achieved. The success of the technology can be attributed to a number of factors such as (a) the wide applicability of the process (odour free antibacterial textile by using nano silver suspensions) to a wide range of textiles (medical establishments, sportswear, daily wear, baby clothing’s, etc). (b) Active involvement with firm in addressing technological challenges (C) Learning from the failure of their water filter

ARCI case study of nano-coating textile also showed the importance of understanding regulatory requirements of other countries as otherwise not addressing them can impede the technology transfer. The company had difficulty in transferring this solution to companies in Europe as they had to strictly follow REACH protocol which defines safeguards and volumes for chemical transfer with nanomaterials treated as chemical substance under this protocol. The important lesson that emerged was the need of the government to provide support to firms to meet regulatory requirement of different countries particularly for large markets such as U.S., European Union.

The institution had also learned from its failure in water filter. In this case from the start itself, there was active innovation collaboration with the firm which latter was visible in commercialization. The problems such as of scaling, technology reaching the expectation level, regulation were jointly addressed by ARCI and the firm.

Emergence of Bangalore as a Nanotechnology Hub

The study finds different stakeholder involved in promotion of nanotechnology in Bangalore. Two established research institutes IISc and JNCASR are the key actors in this cluster. Central and state government both are active players in promoting the nanotechnology. Institutions like CeNSE and INUP are key actors in the system. CeNSE has been able to provide a platform for interdisciplinary research teams to work together. INUP on the other hand is helping in strengthening the skill competency. Linkages between the different institutions and across the other research hubs in India and globally is observed in the Bangalore cluster. Creation of institutions like Vision group has been an important factor in creating linkages among various stakeholders. Particularly important is its linkage with Karnataka government for promoting nanotechnology activities in the state.

Vision group is led by star scientist C.N.R. Rao and comprises other scientists of high eminence like Ajay Sood. Reputed industry players also have central positions in this group. The networks and linkages make the cluster dynamic with events like Bangalore Nano helping to bring the different stakeholders in the city, across the country as well as globally together. Enabling institutions such as Karnataka Startup policy have influenced nanotechnology development in the city. Some firms are emerging from the research institutes however there are large scope of translation from lab to industry. The startup policy can help to drive this activity further, reflections of which is seen from recent study by Balasubhramany (2017). The emergence of Bangalore as a nanotechnology hub reflects many of the key observations of Vinck and Ramani (2014) of their examination of factors that led to the emergence of nanotechnology cluster in Grenoble.

The study has applied a multimethod research approach (i.e. triangulation) to capture the different facets of the nanotechnology development in India. This has helped capture to some extent the multi-facet dimension of India’s nanotechnology development. We have tried to capture the process by figures, stylized facts etc. This approach is influenced by Nelson (2012) who has drawn attention to the need to move beyond “As If” explanations as formal theories do to capture the mechanism of the process. This approach they call as Appreciative Theorizing which tends to be close to empirical substance and empirical work. Appreciative theorizing is closer to the

Innovation System approach we have used in this paper to the extent that processes it specifies are described in a stylized manner. However, as Edquist (2006) cautions Innovation System approach is not an example of appreciative theorizing as it does not provide convincing propositions as regards established and stable relationships between variables. Inspite of this limitation, systems approach does allow one to draw influential insights towards developing policy interventions that can help to bridge the "valley of death". The paper is an attempt in this direction.

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