Capabilities and Governance of Nanotechnology in the Developing World

Insights from India

Editors
Shilpanjali Deshpande Sarma
Manish Anand

The imperative for responsible innovation in the nanotechnology domain has inspired and provoked assorted views on its trajectory, potential implications as well as appropriate pathways for its development across a spectrum of stakeholders. These debates assume greater significance in the context of developing nations since harnessing the inherent potential of this transformational technology presumes the establishment of simultaneous capabilities for cutting-edge technological innovation as well as risk governance, regulation, and public engagement in an environment challenged by limited resources, weak innovation systems, and inadequate abilities for risk management.

This book seeks to examine developments, opportunities, concerns, and challenges in nanotechnology from a developing country perspective raising complex questions and issues in the course of the responsible development of nanotechnology. It covers a range of issues such as potential R&D prospects, S&T capacities and innovation systems, issues of environment, health and safety, risk and regulatory preparedness, and prospective socio-economic and ethical repercussions, with a focus on Indian developments. Based on half a decade of interdisciplinary research and informed by multi-stakeholder insights on the aforementioned aspects, it proposes options for effective and inclusive governance for nanotechnology in India.

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The Energy and Resources Institute

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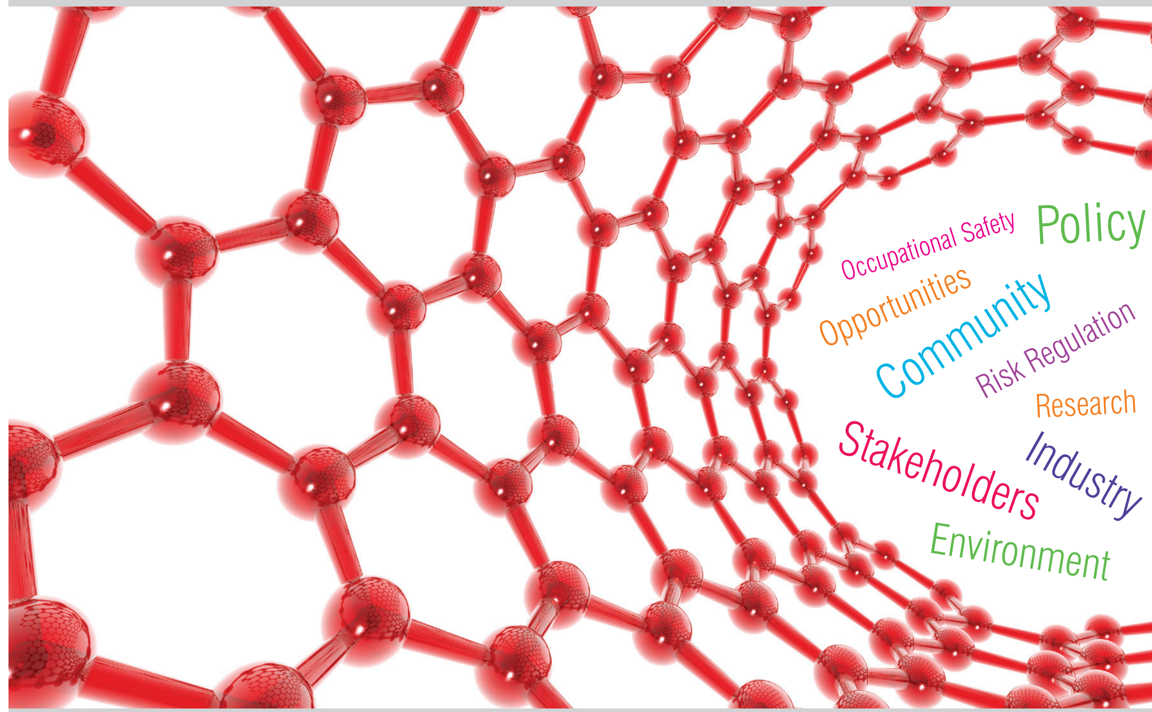

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Foreword

I have had a long association with the Indian nanoscience and technology scene. It is the feeling of the scientific community that India had missed the semiconductor/superconductivity revolution years ago by not taking initiatives and making investments at the right time and so this time around they did not want to miss the bus in relation to nanoscience and technology. That led to the Indian blueprint on the Nano Initiative and subsequently the Nano Science and Technology Mission, of which I was the Mission Director, while working at the Department of Science and Technology as the Head of the Science and Engineering Research Council. India is now witnessing the transition from its capacity-building initiatives in the nanotechnology domain towards the next phase in which a vigorous expansion and advancement in the field is anticipated.

In light of these developments, this publication, *Capabilities and Governance of Nanotechnology in the Developing World: Insights from India*, comes at a very opportune moment for India and probably other developing nations since it lays emphasis on responsible innovation in nanotechnology. For the nanotechnology community in India that is gearing towards the development of concrete applications while anticipating an appropriate regulatory framework and also for other developing nations building on their nanotechnology endeavours, this book could probably clarify the many issues that must be straddled for sustainable and effective outcomes from engaging with nanotechnology. I believe this book is important from the point of view of understanding the social determinants of nanotechnology. It brings forward splendidly the need in this country for scientists and social scientists to work together, if emerging areas like these have to do good to the nation as whole. I have rarely come across a publication which brings together these multidimensional elements in a high technology area, such as this one. Of course, the reader can be the judge of this from his or her own perspective.

I was fortunate to have been associated with the TERI team in its efforts towards this intellectual exercise. This publication is an outcome of half a decade of creative and diligent efforts by researchers at TERI that took the shape of intensive studies, reviews, and wide-ranging stakeholder interactions on diverse issues through dialogues, interviews, and surveys. A particularly interesting exercise was their dialogue in January 2010 on risk governance issues which was attended by scientists, technology developers, risk researchers, and social scientists. The dialogue led to several interesting arguments being placed by the concerned stakeholders. My involvement in such occasions and overall experience has been towards contributing to a balance between technological issues and its implications, particularly in the area of risk management and others of an ethical nature. This book is therefore an outcome of interdisciplinary research efforts and inclusive perspectives, making it a unique literary endeavour.

The book addresses a range of aspects that are extremely relevant to the progress of nanotechnology in the world today. Alongside an appropriate focus on technological benefits, advancements, and national innovation capacities, the authors have also sought to outline issues that societies currently grapple with in relation to responsible development of nanotechnology — environmental, socio-economic, and ethical impacts as well as the accompanying regulatory and governance challenges. The authors offer keen insights for policy and effective multi-level governance of nanotechnology. The book is thus a comprehensive and thought-provoking resource for the curious reader as well as the experienced nanotechnology practitioner or researcher. It offers an informed view of the multiple facets and implications of this revolutionary technology and makes an effective case in favour of the need for multi-layered capacities being developed for responsible innovation. It certainly advances the discourse on nanotechnology and developing societies and will help inform policy-makers and other stakeholders on a wide range of issues.

The issues raised in the book are simple yet profound. While these have been with us for a very long time, they have acquired significance and urgency in the wake of twentieth-century scientific revolutions. Many of these issues and questions have no clear answers as yet, but that should not deter us from asking and trying to find these elusive answers. The book assembled here addresses questions of the sort that all of us ask as children of science and many of us fortunately do not cease to ask as adults. To quote Isaac Newton:

> I do not know what I may seem to the world, but as to myself, I seem to have been only like a boy playing on sea shore, and diverting myself now and then finding a smoother pebble, or a prettier shell than ordinary, whilst the great ocean of truth lay undiscovered before me.

To me this book has revealed new and interesting issues that every student of science should be seriously concerned with.

The TERI team deserves credit for having brought these intricate issues out into open. It is my sincere appeal to all sections of the scientific community to address these concerns while at the same time trying to advance technological developments.

It is a pleasure to have worked with the TERI team. As I have said earlier, the team had a stupendous task of gathering and integrating the multitude of issues related to emerging technologies, such as nanotechnology. I wish to extend my appreciation and best wishes to the TERI team for their hard work and excellent contribution to the field of nanotechnology.

December 2013

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This publication draws on the work conducted over five years by the authors involved in two research studies supported by the International Development Research Centre (IDRC), namely, 'Capability, Governance, and Nanotechnology Developments: A Focus on India' and 'Nanotechnology in South Asia: Building Capacity and Governing the Technology'. The compilation of this book has benefited immensely from interactions with a large number of people. The authors would like to take this opportunity to thank them all.

First and foremost, the authors gratefully acknowledge IDRC for its support over the years, enabling enhanced research capacities on emerging technologies and policy issues. In particular, the authors wish to thank Stephen McGurk, Veena Ravichandran, Ritu Kalia, Sara Ahmed, Margaret Male, and Prabha Sethuraman for their constant encouragement and help.

During the course of the project and in the efforts to build capacities in the complex area of nanotechnology policy and governance issues, the team has gained much from the advisors to the project as well as from interactions with stakeholders. Their insights were invaluable and the authors would like to extend their heartfelt thanks to them. The authors especially thank the Project Leader, Ligia Noronha, for all her contributions, indispensible guidance, and support throughout the project duration. The extended advisory group in TERI also provided much intellectual encouragement in the design and development of this study and the authors express their gratitude to Prodipto Ghosh, S Sundar, and Suresh Babu. We also thank our external advisors Veena Chhotray and Venkatesh Rao Aiyagari for their guidance.

The authors acknowledge the research contributions of project team members — Seema Singh, Jayashree Vivekanandan, and Saswata Chaudhury.

Throughout the process of writing this book, many individuals from the community have taken time out to help the team. Special thanks is due to the reviewers, YP Abbi, Prajit Basu, Sujit Bhattacharya, Arunava Goswami, Nilanjan Ghosh, and Shyama V Ramani for their feedback. This publication has benefited from their inputs and the authors gratefully acknowledge their support and guidance.

During the conception and the actual writing of this book, the team relied on the support of colleagues at TERI. Therefore, the authors would like to especially thank all colleagues who have contributed to bringing this publication in its final form; many thanks to Shenoy Mooken for his secretarial assistance and Shikha Ranjha for her help with the chapters. The authors are also grateful to Arpita Dasgupta, Hemambika Varma, Roshni Sengupta, Rajiv Sharma, Santosh Singh, RK Joshi, Santosh Gautam and other colleagues at TERI Press for their editorial and other inputs.

Finally, the authors thank their families for their support and understanding during the course of the development of this publication.

CHAPTER 1

Introduction

Shilpanjali Deshpande Sarma and Manish Anand

Four technologies are going to drive the future world and future India — biotechnology, nano- technology, information technology and environment technology.

APJ Abdul Kalam
Ex-President of India (2002–07)

Likewise nanotechnology will, once it gets under way, depend on the tools we have then and our ability to use them, and not on the steps that got us there.

K Eric Drexler
Engineer and 'Founding Father of Nanotechnology'

I am certain that nanotechnology holds huge promise. In medicine. In energy. In computer processing. In so many areas. But unless environmental, health, and safety issues are addressed in a way that fosters public understanding and support for nanotechnology, that potential is in jeopardy.

Ron Wyden
Senior United States Senator, Oregon

The big revolution of the small is being shaped at our doorstep. The technology that seeks to harness the unique properties of nanomaterials that are about one-billionth of a metre is moving from the realm of science fiction to reality in developing country contexts. Nanotechnology, an interdisciplinary technology that deals with the controlled manipulation of matter at the nano-scale to develop products, devices, systems, and applications with novel or improved functionalities is now well entrenched in the science and technology (S&T) policies of India and other developing nations. India has embarked on a mission mode programme called the Nano Science and Technology Mission (NSTM) in 2007 and has been granted funds to the tune of INR 1,000 crore (approximately US$ 254 million). Nanomaterial-utilizing applications such as refrigerators, water filters, air sanitizers, cookware, paints, textile, cosmetics, health care products, and even pharmaceuticals are now being manufactured and/or marketed in India. Other developing nations such as Sri Lanka, South Africa, and Brazil have similar programmes and are anticipating the commercialization of nanoproducts.

Nanotechnology is expected to revolutionize industrial and commercial set-ups in the coming years in various domains including material engineering and manufacturing processes, information and communications, electronics, pharmaceuticals, food processing, textiles, and others. Besides the economic benefits that nanotechnology can bestow, scientific endeavours in this field are anticipated to contribute significantly to the spheres of health, agriculture, water treatment, energy production, environmental monitoring and remediation. Based on the experience of the last decade, a greater demand for nanomaterials and nanoproducts can be anticipated in the future. Already in their latest research study, 'Nanotechnology: A Realistic Market Assessment', BCC research analysts have anticipated the size of global nanotechnology market at $48.9 billion in 2017. Consequently, the promise of the socio-economic benefits that can be derived from nanotechnology has resulted in both developed and developing country investment and R&D engagement with nanotechnology. Currently, over a thousand nanomaterials utilizing products have been commercialized worldwide.

Our study on nanotechnology and policy in developing countries has provided occasion for many an interesting debate and discussion on development of emerging technologies involving stakeholders from a variety of disciplines and sectors. What has emerged from these deliberations, and which is usually obscured from technology debates in developing nations, is that nanotechnology is more than the sum of the outcomes of the pursuits in S&T development. As essential as these facets are to the advancement of nanotechnology, equally important is the fact that nanotechnology development is embedded in society and exists within a prevailing realm of networks, values, and decision-making capacities that impinge on its development, making the context as significant as the science itself. This begets the following questions: What opportunities and challenges does an emergent technology such as nanotechnology present to India and other developing countries? And, how can developing countries such as India engage with such technologies in a responsible manner? This book tries to address these crucial aspects concerning nanotechnology in the developing world with a focus on India.

As R&D advances in the nanotechnology domain, there is now focus towards application-oriented research in addition to basic research. Given the imperatives for facilitating technology development in the spheres of clean energy, water filtration, drug delivery, and environmental protection, there is much anticipation for the contribution of nanotechnologies in these domains. Nanotechnology opens up possibilities for improving and facilitating the widespread use of alternative energy options such as photovoltaic cells, hydrogen fuel cells, electric vehicles, and the like, enabling reduced dependence on fossil fuels. It also creates avenues for precision delivery of nutrients and plant protection chemicals during crop production improving efficiencies and reducing wastage. Targeted delivery of drugs, superior diagnostics, and nanomaterial-enabled prosthetics can help revolutionize medical science. Advanced technological interventions in the spheres of water and wastewater treatment, mitigation of air pollution as well as detection of environmental contaminants are some of the other prospects nanotechnology can enable. Since scientific progress in these spheres is intrinsically linked to human welfare and sustainable development, harnessing nanotechnology as a potential tool to address development needs offers an excellent opportunity for developing nations grappling with resource depletion, energy, and poverty issues to meet societal challenges.

Although nanotechnology comes with great promise, transforming nanotechnology's potential into tangible and beneficial outcomes necessitates creation of innovation systems. Innovation in the context of nanotechnology development would involve directly or indirectly a large variety of actors, including firms, research organizations such as universities and public and private research centres, financial institutions, regulatory authorities, and consumers. An institutional environment must be facilitated that enables interaction among various actors and explores policy options for application of new technologies. New products, processes and services created using nanotechnology would involve social, economic, ecological, political, and ethical matters surrounding their emergence. These aspects must be sufficiently addressed in defining a responsible trajectory for nanotechnology innovation.

Responsible innovation and equitable development is vital for eliciting sustained benefits from nanotechnology. Nanotechnologies, due to their unique functionalities and transformational potential, can impact ecosystems and existing social milieus. While the risk-benefit dilemma in relation to utilization of technologies has been experienced with the advent of previous technologies, those emerging from nanotechnology could be unique in some aspects. Nanotechnology enables manipulations at the building blocks of life and convergence of emerging technologies allowing significant transformations in multiple and diverse sectors. Therefore, the degree of complexity that could be experienced and would need to be managed in developing nanotechnology is likely to be greater as would the potential impacts.

Given the unusual physio-chemical priorities, size, and structural transformations possible with nanomaterials, nanotechnology applications may pose safety concerns to society in the absence of adequate risk governance measures. Developing nations such as India might be more vulnerable to the risks as they lack necessary resources as well as adequate capacities for dealing with environment and health issues. As nanomaterial R&D and manufacturing expand and as nanoproducts and applications reach the market place, adequate methods for anticipating, mitigating, and managing risks is essential as is fostering inclusive governance measures with stakeholders and the public. Despite growing research on toxicity and exposures, key knowledge gaps still exist on the nature, extent, and likelihood of risk manifestation from nanotechnologies in real world scenarios, given challenges in the realm of metrology, risk assessment methodologies, standard development and others. The emphasis within developing nations like India to avail opportunities from nanotechnology in face of these knowledge gaps and without formulating adequate responses to uncertainties has resulted in delays in developing comprehensive risk governance mechanisms. Global efforts for effective risk evaluation and regulation of nanotechnologies are gaining pace alongside pathways for greater stakeholder engagement and cooperation. India too will need to develop capacities for anticipatory governance of nanotechnologies for availing the benefits and avoiding potentially adverse environmental and health consequences.

In addition to environment and health concerns, the far-reaching and extensive potential of nanotechnology applications also raises questions of socio-economic and ethical dimensions. Issues of equity in relation to access to potential benefits, distribution of benefits and risks as well as those related to risk communication, stakeholder engagement, and inclusion of stakeholder perspectives in various levels of decision making in nanotechnology development are central to responsible innovation. On the other hand, there has been speculation on the ability of nanotechnology to cause shifts in the way goods are manufactured and produced. It is possible that nanotechnology could replace commodities or enhance commodity use in developing nations. This may have significant socio-economic repercussions — positive or negative — in nations dependent on commodity trade. Although more in the realm of the future, it is vital that developing nations that are resource rich engage with these aspects in order to forecast developments in nanotechnology, develop strategies to exploit potential opportunities for commodity-based industries as well as build resilience to avoid potentially adverse outcomes.

Given the complexity, transformative nature and multifaceted implications of nanotechnology, a more extended notion of capability both in terms of what exists, and what needs to be there is necessary for responsible development of this technology. A grounded understanding of resources, options, and skills is needed to engage with and govern nanotechnology developments in developing nations such as India. Adopting a holistic capability and governance approach would enable integration of relevant perspectives on issues, challenges, prospective emerging applications, and other factors that will be influential in determining the development pathways for nanotechnology. A comprehensive governance framework has to transcend all the vertical and horizontal levels involved in the development and application of such technology. The horizontal level refers to distributed responsibilities among national government departments, statutory bodies, and other non-government groups in engaging with nanotechnology developments; capabilities; environmental, health, socio-economic, and political impacts, and designing a regulatory framework. At a vertical level, the framework spans global, regional, national, state, and local nanotechnology developments and policy making.

About This Book

This book titled *Capabilities and Governance of Nanotechnology in the Developing World: Insights from India* addresses various dimensions and complexities of nanotechnology development. Through its chapters, this publication explores the landscape of nanotechnology developments in India and also examines the opportunities, concerns, and challenges that this socially transformative technology can present from a developing country perspective. The authors through their respective chapters cover themes as diverse as potential R&D prospects, innovation frameworks, risk governance and regulation, S&T capability, and multi-level governance offering various options and imperatives for India's effective engagement with this technology. Overall, the thread that binds the various themes that the book addresses is the need to enhance national capacities to responsibly engage with nanotechnology in developing country contexts. The book describes a framework for inclusive and effective governance for nanotechnology in India.

Significantly, the contents of the book mainly draw on the research undertaken in the project 'Capability, Governance and Nanotechnology Developments: A Focus in India' that has been supported by IDRC. This research was undertaken in an interdisciplinary manner with researchers from backgrounds as diverse as S&T, environmental science, science policy, law, social science, and economics. It was also informed by interactions with experts and a series of multiple stakeholder dialogues on various facets of nanotechnology development. This book therefore seeks to present to its audience a unique literary endeavour that reflects the holistic assessment of nanotechnology in all its dimensions, facilitating insights for the governance of nanotechnology in developing countries in its analysis.

The book raises very complex questions and issues in the responsible development of nanotechnology, particularly in the context of developing countries, such as India. We invite you to explore this world of nanotechnology and its development through the lens of responsible innovation and governance readiness in the developing world.

CHAPTER 2

Emerging Innovation Systems of Nanotechnology in India

Manish Anand and Shilpanjali Deshpande Sarma

2.1 Introduction

Nanotechnology promises to deliver novel products and processes or enhance the performance of existing ones across sectors. They include interventions in a range of domains such as water, energy, health, agriculture, and environment that could create solutions for several development-related problems, especially in developing countries (Salamanca et al., 2005). Though shrouded in a lot of hype, several industry-related sectors such as pharmaceuticals, electronics, automobiles, textile, chemicals and manufacturing sector, information technology, and communications as well as biotechnology appear poised to gain from nanotechnology applications.

Nanotechnology is currently being pursued by nations with a buoyant and high technology drive. Globally, investments have been made, nanotechnology programmes initiated, and R&D activities have commenced. The US National Science Foundation has listed it as one of six priority areas; it is one of the themes in the European Union (EU) Framework Programme for Research and Technological Development in Europe, and it has been the focus of research in countries worldwide. Markets worth US$ 1 trillion have been forecasted in 2015 and it is expected that nanotechnology-derived revenues will attain 15% of projected global manufacturing output ($2.6 trillion) in 2014 as compared to 0.1% in 2006 ($50 billion).

In light of the developments worldwide hailing nanotechnology as a technology with the potential of addressing a number of developing country needs, India has sought to promote nanotechnology applications in sectors that are likely to have a wide impact, and influence the course of future development in the country. However, there is a knowledge gap in terms of having an overall perspective on nanotechnology developments, players involved, and their role in shaping its trajectory in the Indian context from an innovation systems perspective.

This chapter attempts to map and describe contours of the innovation system in India, within nanotechnology, by delineating the actors, networks, and institutions and examining the issues and challenges posed to the innovation system in delivering nanotechnology innovation in a responsible manner. Section 2.2 describes nanotechnology, its various sub-fields and application area. This is followed by an introduction to innovation systems approach and its relevance and meaning in the field of nanotechnology. Section 2.5 situates nanotechnology in the Indian innovation system in terms of its actors, frameworks, and institutions that have led to the emergence of this high technology field in India and are also currently instrumental in shaping it. Section 2.6 concludes the chapter with an assessment of various issues and challenges posed to the Indian innovation system with respect to engaging with nanotechnology in a responsible way.

2.2 Understanding Nanotechnology

Nanotechnology is defined as the design, production, and application of structures, systems, and devices through control at nanometre scales (Royal Society and Royal Academy of Engineering, 2004). The term nanotechnology represents a variety of technologies with potentially different applications that nevertheless, at a fundamental level, share the common feature of either incorporating nano-scale materials or having evolved from processes at the nano-scale. At this scale, which is 1 billionth of a metre, materials display properties and functions that are different from their larger analogues, and it is these unique properties that nanotechnology aims to exploit in order to create novel applications or enhance functions of existing products or processes. While definitions might vary slightly, a broad consensus has evolved that nano-scale refers to dimensions between the range of 1–100 nm. The scientific foundation for nanotechnology stems from the field of nanoscience which involves the study of the phenomena and manipulation of materials at nano-scales.

In order to make comprehensible the minuteness of objects in this range, researchers have found it useful to compare nanodimensions to objects belonging to a similar bandwidth with regard to size. For instance, the most popular comparison is that of a nanometre to the human hair, the former being 100,000 times smaller than the diameter of the latter. One nanometre is also approximately 1,000 times tinier than average-sized bacteria, which resides in micrometre dimension. Figure 2.1 illustrates the position of the nano-scale with respect to other dimensions.

Nanomaterials by virtue of their size and physical structure exhibit unique behaviour; for instance, unusual optical, magnetic, and electrical properties as well as increased reactivity due to enhanced surface area. This leads to new functions in nano-scaled materials although they may share chemical compositions similar to their larger analogues. Gold, for example,

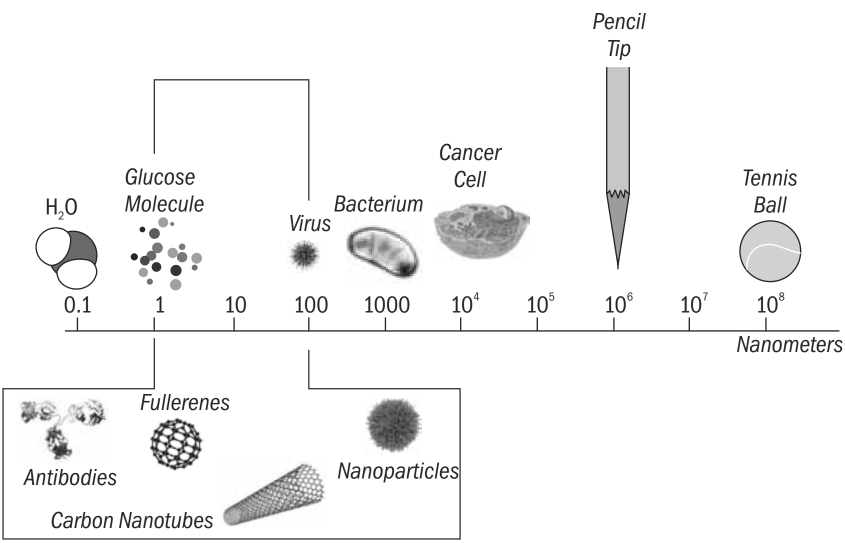

Figure 2.1: Understanding nano dimensions
Source: International Iberian Nanotechnology Laboratory (INL), Portugal. See, http://inl.int/what-is-nanotechnology-2

shows a change in its optical properties and turns red at nanodimensions. Further, depending on its specific size at the nano-scale, it could also display other colours such as green, purple or orange. In another illustration, sunscreen applications, incorporating bulk zinc oxide or titanium di-oxide are traditionally characterized by their white coats on account of these materials being opaque to visible light. However, when their nano-version are utilized, the sunscreens exhibit transparent properties. On the other hand, nanotechnology has also made possible the creation of materials that have not previously existed in material science. Carbon nanotubes, made from rolled carbon sheets or graphite about 1 atom thick is one such example. Carbon nanotubes can act as conductors of electricity or semiconductors based on their 'chirality' whereas graphite at the macro-scale, one of the most widely used forms of carbon, does not conduct electricity. It is predicted that as capacities to operate and manipulate at the nano-scale improve, more complex systems and devices with improved functions could evolve from research at the nano-scale.

Overall, the unique abilities of nanomaterials, together with tangible capacities to harness them, has created significant interest within academia, industry, and policy circles in developed and developing nations towards its various applications. Nanotechnology, it is perceived, could revolutionize the industry and generate economic progress by enabling advances in material science and chemical engineering, manufacturing, pharmaceuticals, information and communication, electronics, and defence sectors. More significantly, tremendous benefits to society have also been anticipated from its applications in spheres such as health, water, renewable energy, agriculture, and environment. Linkages to achieving the Millennium Development Goals (MDGs), improving socio-economic progress, and addressing development-related challenges, with respect to developing countries engagement with nanotechnology, have been established. Nanotechnology can lend itself to several other technologies and the convergence of this emerging field with biotechnology, information technology, and cognitive science could enable technological advances and social transformations previously unseen in history. For this reason, as well as the broad spectrum of sectors it might provide opportunities for, nanotechnology has been hailed as an enabling and transformative technology.

2.3 Nanotechnology Innovation System: Framework and Dynamics

2.3.1 Innovation system approach and nanotechnology

Developed in the late 1980s and early 1990s, the innovation system approach emphasizes innovation as a dynamic process, arising out of the interactions between different actors and involving knowledge flows as well as market interactions. The concept of innovation systems looks at innovation — viewed conventionally as a linear process driven by research — in a systematic, interactive, and evolutionary way, whereby networks of organizations, together with institutions and policies that affect their innovative behaviour and performance, bring new products and process into economic and social use (Freeman, 1987; Lundvall, 1992; Edquist, 1997). These systems which are open and heterogeneous could have different units of analysis that are national (Lundvall, 1992), sub-national, regional (Cooke et al., 1997), local, sectoral (Lundvall, 1992; Malerba 2002), technological (Carlson and Stankiewicz, 1991), and so on, and could be further extended for analysis at the international level given the increasing dependence on international information exchange and collaboration (Fromhold-Eisebith, 2006).

The innovation system approach provides a heuristic tool for studying generations of nanotechnology innovation. As nanotechnology has a wide application potential in different economic sectors, we can say that the innovation system for nanotechnology is characterized by multiple innovation systems which are at different stages and are contingent upon actors and frameworks existing in a particular sector of application. Also, it follows that actors and networks are increasingly spread across national and sectoral boundaries. A new mode of knowledge production, termed as Mode-2 by Gibbons et al. (1994), characterized by application-oriented knowledge production on a transdisciplinary basis involving multiple actors, locations, and skills is very much evident in the case of nanotechnology. In this scenario of distributed system for innovation with diffused boundaries and sectors, it is not really possible to discuss multiple nanotechnology innovation systems. Nevertheless, this chapter deals with the nanotechnology innovation system in India in general by describing the structure, institutions, actors, and mechanisms which generate innovations in this domain.

Nanotechnology innovation system could be conceptualized as a system of innovation wherein research performed in a variety of scientific disciplines supports technological development having applications in different economic sectors (Figure 2.2). The domain of nanotechnology derives its strength from basic research in physics, chemistry, and of late, biology, and the research carried out in these fundamental disciplines that have resulted in new technologies altogether. For instance, quest for new properties in materials in case of nanomaterials technology, increased efficiency at smaller size in electronics, construction of nanostructures through biomimetics, regenerative medicine in the case of biotechnology, and manipulation of light waves in optics have resulted in the advancement of nanotechnology. The interfaces between these fields and technologies have innumerable applications in various economic sectors.

A generic framework of nanotechnology innovation system is provided in Figure 2.3. In the framework, the main systemic interactions between the actors are represented in terms of knowledge, funding, and influence flows.

Of the various actors in the innovation system, academic and research organizations as well as technology developers and knowledge-sharing networks constitute an important category influencing the process of innovation. Scientific discoveries and the knowledge generated at academic and research organizations may pave the way for numerous innovations and industries. Manufacturers rely on knowledge and research organizations to overcome manufacturing problems. Also, instrumentation, lab techniques,

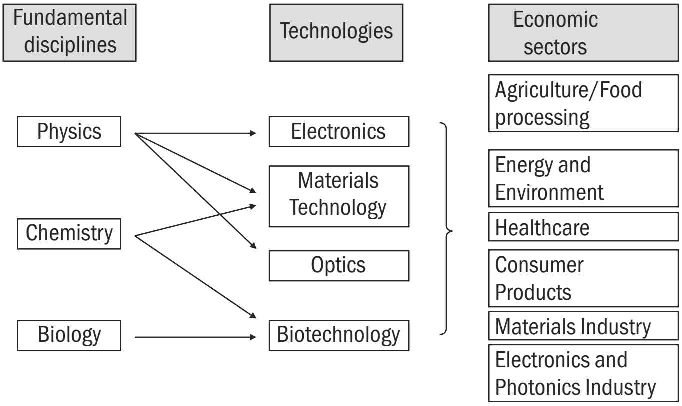

Figure 2.2: Schematic representation of disciplines, technological applications, and economic sectors of the nanotechnology innovation system
Source: Adapted from Perez and Sandgren (2008)

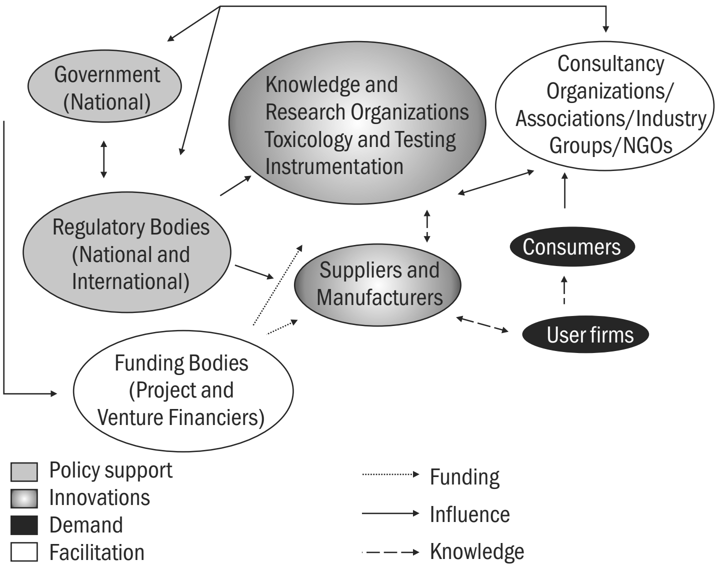

Figure 2.3: Generic framework for nanotechnology innovation system
Source: Anand (2009), adapted from Foxon et al. (2005)

and analytical methods that are developed in pursuit of basic research eventually find their way into the manufacturing process. Another important set of actors are the user firms and end-users/consumers. The user firm, specialized in a variety of sectors, uses knowledge in the form of commercial products for consumers. National government and regulators, research funders and financial investors, responsible for setting the framework conditions constitute the third set of actors. National governments play an important role in promoting research through funding bodies and in regulation via regulatory agencies. Besides the national government, there are a number of organizations both at international and national level influencing nanoinnovation. International standards, such as the International Organization for Standardization (ISO) and international institutions, such as the Organisation for Economic Cooperation and Development (OECD) and the World Trade Organization (WTO) comprise one set of key players while consultancy organizations, industry associations, and civil society organizations form another set.

2.4 Dynamics of Innovation in Nanotechnology

The key feature of a nanoinnovation system is that the process of innovation in nanotechnology would vary dramatically across sectors and product lines. In science-based industries, such as pharmaceuticals, the primary driver of innovation is breakthrough in scientific research, while in the technological field of electronics, innovation depends on product and process development. Therefore, to understand the processes and systems of innovation, it would be crucial to map the heterogeneous and distributed network of actors according to the sectors and applications.

A second key feature of nanoinnovation system is that innovation in nanotechnology would require knowledge and research organizations to work in an interdisciplinary mode. This is because many research breakthroughs in nanotechnology are stimulated in the intersection of established scientific disciplines and across fundamental and applied technological research. Therefore, inter-institutional collaboration, combining scientific knowledge from various disciplines in universities and laboratories, is an important dimension of performance in the emerging field of nanotechnology. Further, collaboration between firms and public research institutions can play an important role in advancing nanotechnology by marrying public sector research capabilities with financial resources of the private sector.

Another characteristic of the nanoinnovation system is that the cross-sectoral application potential of nanotechnology would require firms, depending on their capability, to take decisions on whether to focus on one technology or market structure or rely on cross boundaries between different nano-scale technologies. In this regard, according to Meyer (2006), firms will have to undertake strategic decisions on whether to:

- occupy a technological niche and apply their proprietary technology to one specific application area;
- build on a base in several nanotechnology areas, and by integrating technology and expertise in more than one nanotechnology area, develop solutions for one area of application;
- pursue an approach that champions customizing expertise and technology to a range of different application areas; or
- combine expertise in more than one nanotechnology with more than one application area.

Thus, in case of nanotechnology because of its nature and characteristics, a greater degree of interactions between firms and their institutional environments have been foreseen and suggested for successful technology development and diffusion. The institutional environment influence firms' performance by defining its interaction pattern with other actors, such as suppliers and end-users, and the differences in these environments influence substantially the rate and direction of innovation across geographical boundaries and sectors.

2.5 Emerging Innovation System of Nanotechnology in India: Actors, Framework, and Dynamics

2.5.1 Mapping the system

This section maps the various actors, their interaction patterns and the evolution of institutions defining the trajectory of nanotechnology in India. Although still at a nascent stage, the nanotechnology innovation system in recent years is characterized by increased nanotechnology activity in terms of R&D and technology development and commercialization. Public sector R&D institutions are at the helm in the nanotechnology innovation landscape in India.

2.5.1.1 Knowledge and technology base

Nanotechnology in India has its origins at the beginning of this century with the formal launching of Nano Science and Technology Initiative (NSTI) in 2001 by the Department of Science and Technology (DST). The focus areas of the NSTI, as up till 2006–07 are as follows: support R&D projects in nanotechnology; establish Centres of Excellence (CoE) and strengthen characterization facilities; develop human resources; promote international collaborative programmes; and initiate joint institution–industry-linked projects and public–private partnership (PPP) activities. During the five years of NSTI, there was a significant capacity development in nanotechnology owing to the establishment of CoEs in various R&D laboratories and universities across India. A considerable number of research projects—about 100—were funded across various R&D institutions in India under the initiative by the DST. Most of the funding pertained to fundamental

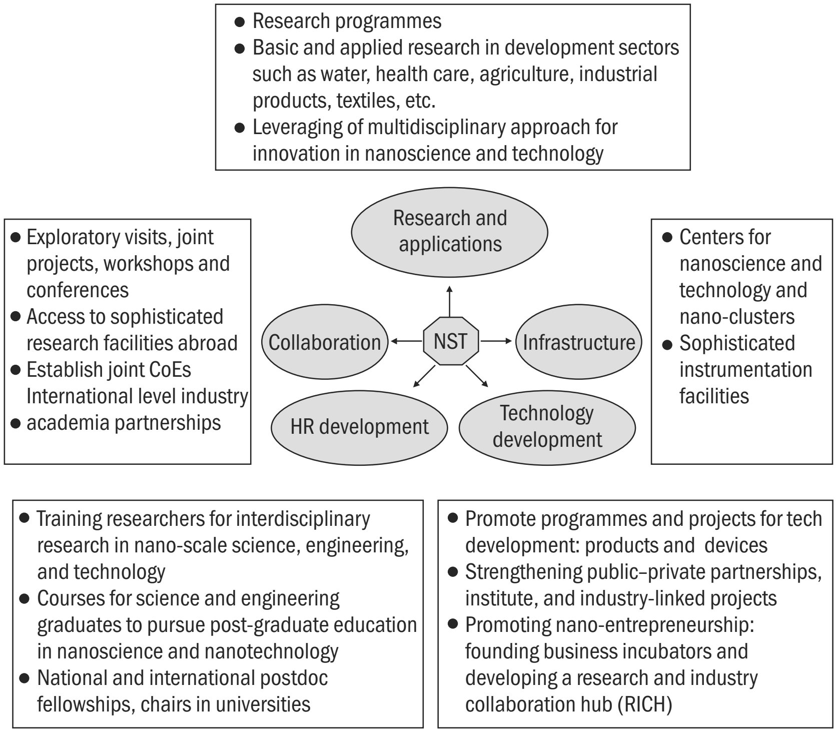

Figure 2.4: Thrust of National Nano Science and Technology Mission (NSTM)
Source: http://nanomission.gov.in

research in nanosciences and the procurement of specialized equipment related to nanotechnology such as atomic force microscopy (AFM), scanning electron microscopes (SEM), and transmission electron microscopy (TEM). Subsequently, increased emphasis has been placed on application-oriented research and product development in the Nano Mission programme, 'Nano Science and Technology Mission' (NSTM), started in 2006–07, with a budgeted outlay of about INR 10 billion for 2007–12. The activities being pursued in the focus areas of NSTM led to further building up of scientific and technological capability in the realm of nanoscience and technology in India (see, Figure 2.4 for thrust areas and activities under NSTM). It would be important to mention that besides DST, there are also other governmental agencies such as the Council for Scientific and Industrial Research (CSIR), Department of Biotechnology (DBT), Department of Information Technology (DIT), Defence Research Development Organisations (DRDO), Indian Council of Medical research (ICMR), and Indian Space Research Organisation (ISRO) that contribute to development of knowledge and technology base of nanotechnology in India.

The bulk of knowledge and the technology base in nanotechnology, is oriented towards the synthesis, characterization, processing, and development of an understanding of the unique properties of nanostructured materials. This is evident from the distribution of projects supported through NSTI and NSTM in different areas in which basic and applied research or product development has been undertaken (Figure 2.5). Research on a variety of nanomaterials — metallic, metal oxide, semiconductor, magnetic nanoparticles, quantum dots, carbon nanotubes and other nanocomposites, polymeric nanomaterials, nanofilms, nanowires, nano alloys, nanoporous solids — have been undertaken and a wide range of routes for synthesis of nanomaterials such as sol-gel, salvo-thermal, spray pyrolysis, chemical vapour synthesis, etc., have been explored. Also,

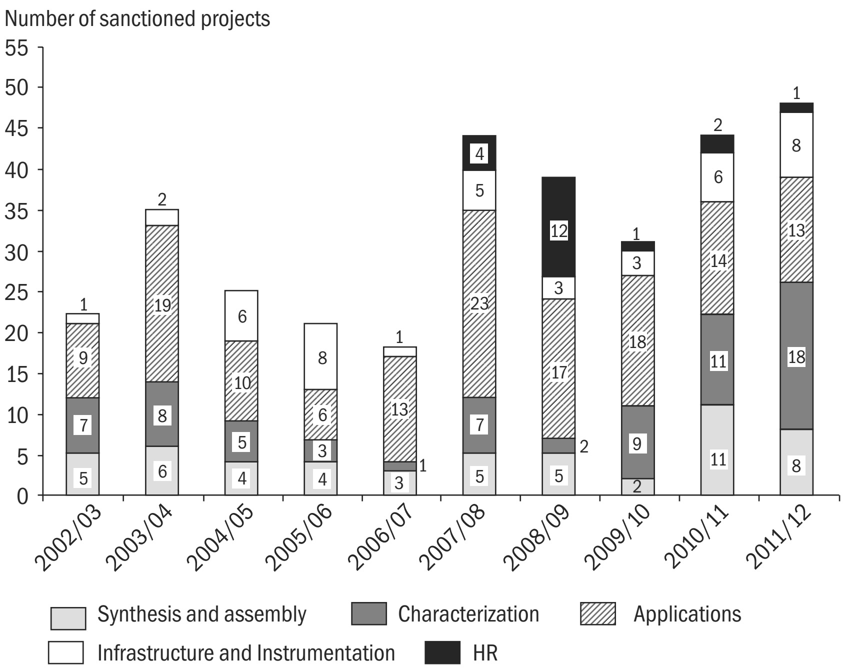

Figure 2.5: Distribution of projects supported by DST through NSTI and NSTM across basic and applied research/product development and other areas
Source: http:/nanomission.gov.in and http://dst.gov.in/scientific-programme/ser-serc.htm

emphasis has been placed on exploring the industrial applications of these materials, besides focusing on development of nanolithography and nanofabrication techniques. Furthermore, a significant number of projects have been supported in basic and applied research in the area of physical and chemical sciences. For example, in the physical sciences, nanotechnology research in India covers broad areas under condensed matter physics and materials science as well as plasma, high energy, nuclear physics, astrophysics and nonlinear dynamics, and laser, optics, atomic, and molecular physics.

Application-oriented research in nanotechnology in India is focused primarily in the areas of health, energy, and environment (Figure 2.6). For example, in the area of health, there has been considerable research focus on targeted drug and gene delivery (therapeutics), diagnostic systems and biosensors, as well as the use of biomaterials for various applications including regenerative medicine. Significant technological achievements

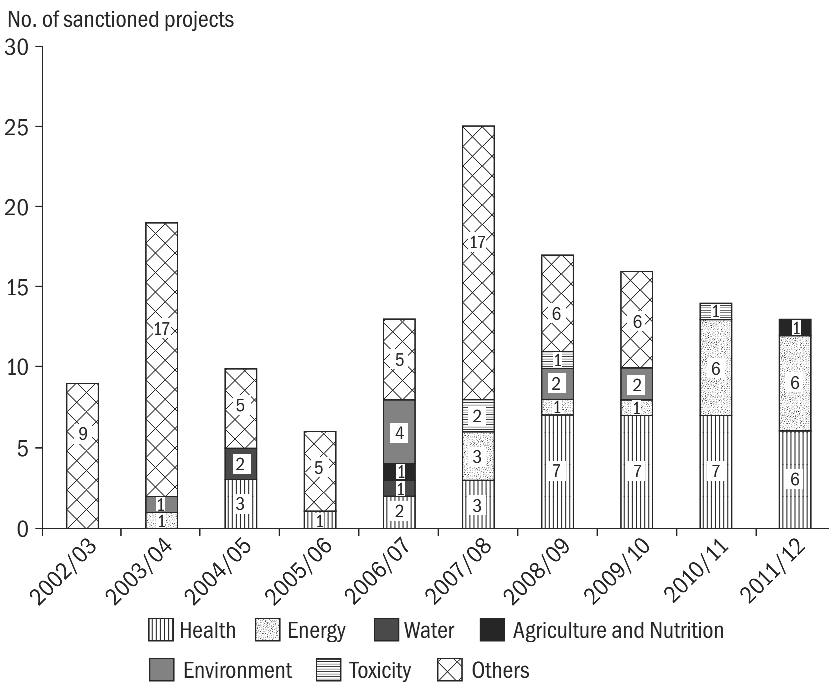

Figure 2.6: Distribution of application-oriented R&D projects supported by DST through NSTI and NSTM across different sectors and other areas
Source: http:/nanomission.gov.in and http://dst.gov.in/scientific-programme/ser-serc.htm

have been achieved in this application area; e.g., encapsulation of water-soluble drugs using hydrogen nanoparticles developed through the reverse micelles-based process. The application of nanomaterials, particularly nano-scale silver and carbon nanotubes, in water purification has been attempted in order to provide access to clean drinking water and various technologies have been developed in this area, such as incorporation of nanosilver in traditional candle filters for disinfection, nanosilver based carbon blocks for pesticide removal, nanosilver coated alumina catalyst for controlling microorganisms in water, carbon nanotube filters for bacteria removal, and nano iron oxide/mixed oxide for arsenic removal. Similarly, in the energy sector, the major area of R&D focus in the nanodomain — which is still in the development and early demonstration stage — is in the arena of solar photovoltaic primarily aiming at development of new materials, processes, device structures, and modules using multicrystalline silicon, thin film, polymers, nanoparticles, nanorods, quantum dots, etc. The basic aim being to improve solar photovoltaic process efficiency, reduce the cost of solar cells, and search for alternate semiconductors in lieu of silicon shortage.

Also, publications and patents in the nanodomain portray the canvas of knowledge and technology base in this emerging area. Bhattacharya et al. (2012) observe that in 2009, India was in the seventh place globally and accounted for 5 per cent of total world production in nanotechnology publications. With regard to the knowledge base of nanotechnology in India, publications in nanotechnology for the period 1990–2009 displays a wide spectrum of knowledge and research base in the area of nanofibres, smart textiles (nanotextiles, yarns, garments, and fabrics), nanocomposites, nanofilteration (industrial effluents), nanoparticles, nanocoatings, nanoapplications (dyes, chemicals and finishes), and general nanotechnology contributions relating to textiles (Karpagam, 2011). Similarly, Bhattacharya et al. (2012) examine the patents issuing from India in the US Patent Office (USPTO) under the class '977' signifying affiliation to nanotechnology and identify 12 filings between 2000 and 2009 out of which 7 have been granted. The major technology areas of patenting in nanotechnology include applications related to drugs and pharmaceuticals, chemical science and technologies (e.g., catalysis), colloid chemistry, separation and non-metallic elements and materials, analysing materials by determining their chemical or physical properties, and methods/filters implantable into blood vessels.

Thus, it is observed that India has built a significant knowledge and technology base in the area of nanomaterials which has found application in different sectors including ones that can address developmental challenges with respect to health, drinking water, energy, etc.

2.5.1.2 Actors and networks

Public sector R&D institutions

Public sector R&D institutions predominating the R&D landscape is largely constituted by the CoE for Nanoscience and Technology established under the NSTI by DST (Figure 2.7). Together, the 19 CoEs and the proposed three

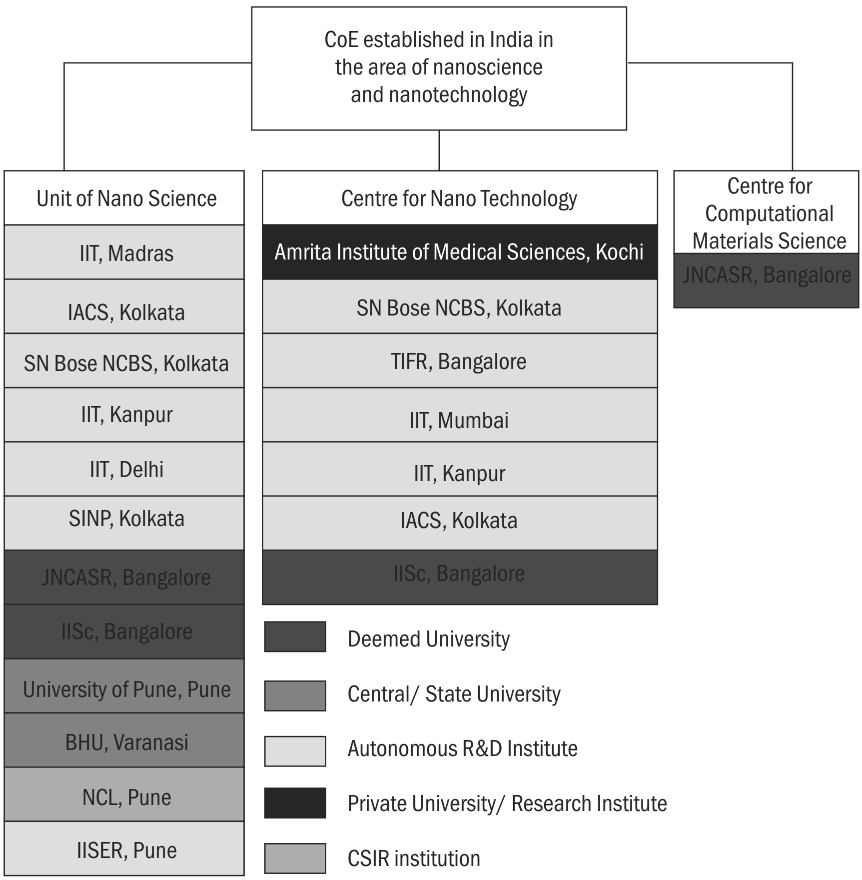

Figure 2.7: Centres of Excellence established in India in nanoscience and technology

Institutes of Nano Science and Technology (INST), one each at Bangalore, Kolkata, and Mohali, are being developed as specialized centres to address the complexities of engaging in diverse R&D in the nano S&T domain. There has been tremendous thrust on nanomaterials by DST. Figure 2.8 lists the research institutes in India and their focus research area.

Discussion with policy-makers has led to the understanding that these CoEs have been set up primarily at those institutes that have either been engaging in nanotechnology-based R&D prior to their establishment or have developed the resources to do so. The SN Bose National Centre for Basic Sciences

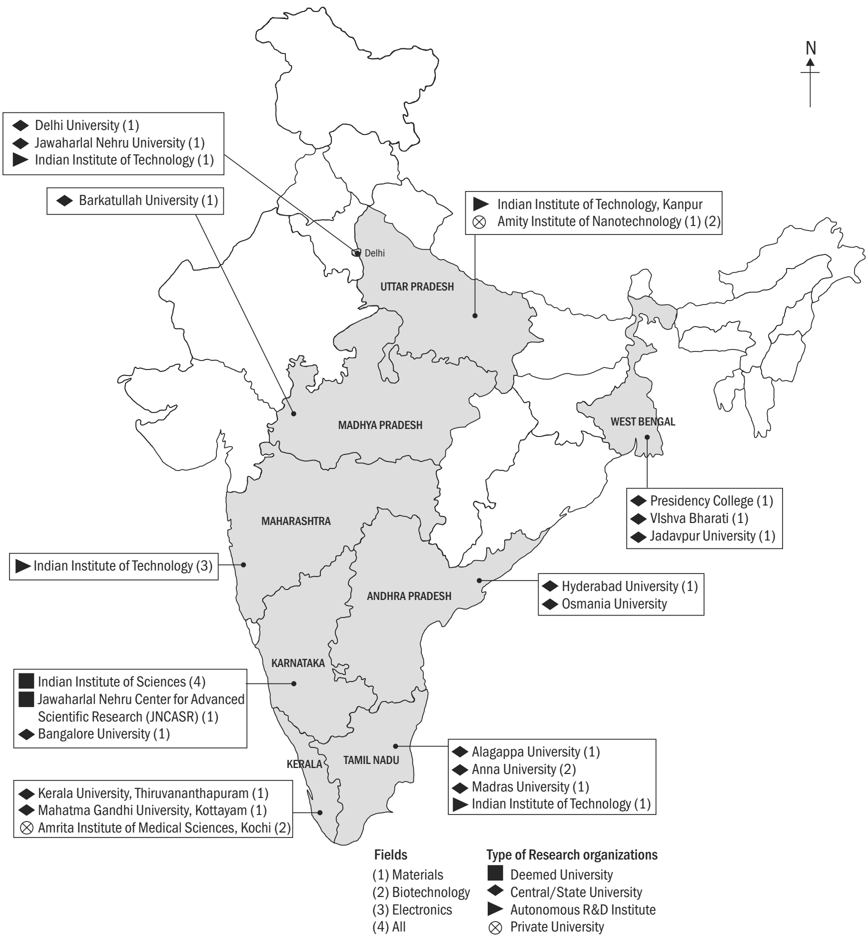

Figure 2.8: Public sector nanotechnology research in India
Source: Author's compilation

(SN Bose NCBS), Indian Association for the Cultivation of Science (IACS), the Indian Institute of Science (IISc), Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), and IIT-Kanpur, each host a Unit of Nanoscience as well as Centre for Nanotechnology. These CoEs as well as others at the IITs — Mumbai, Chennai, and New Delhi — are considered amongst the leading institutes for nano S&T research.

Aside from the DST, the DIT has also supported the establishment of a Centre of Nanoelectronics at IISc Bangalore and IIT-Mumbai. An amount of INR 0.99 billion will be invested in this centre for a duration of five years. Another DIT-supported project, Generic Development of Nanometrology for Nanotechnology, was undertaken at National Physical Laboratory (NPL), New Delhi, which was also developed with a focus on developing calibration and other techniques. An amount of INR 0.11 billion crore has been allocated for this purpose for four years. It is intended that facilities at these centres would be available to other researchers and industry as well. The DBT also appears to be interested in developing CoEs in nanobiotechnology. Apart from these institutes, others involved in nano S&T include CSIR labs such as Centre for Cellular and Molecular Biology (CCMB) (Hyderabad) and National Institute of Pharmaceutical Education and Research (NIPER) (Chandigarh) as well as universities such as the University of Delhi (Kulkarni, 2006).

Industry

Although nanotechnology is at an emergent stage, the presence of a small number of suppliers, manufacturers, and user firms across various sectors in which nanotechnology has found application potential has led us to assume that there exists an emerging nanotechnology innovation system in India. It could be emphasized herein that the growth and trajectory of the innovation system of nanotechnology in India is sector-dependent and would thus require sector-specific policy interventions.

The nanotechnology industry comprises a group of firms involved in bringing nanotechnology processes, materials, tools, and devices into the market (Miller et al., 2005). Different types of firms co-exist actively working in the area of nanotechnology in India. On one hand, there are start-ups which focus mainly on nanotechnology; on the other hand, there are certain established companies that have tried to engage with nanotechnology either to improve their existing product line or to explore businesses for the next generation. Figure 2.9 maps these set of industrial players in nanotechnology in India, along with the fields in which they specialize.

Materials and surface engineering, biotechnology, electronics, and instrumentation and equipment are the nanotechnology fields which have received considerable attention from Indian companies. Following global trends, nanomaterials are the major points of focus of most Indian companies; there exist both established companies as well as start-ups in materials and surface engineering. Monad Nanotech Pvt. Ltd., Innovations Unified Technologies, INNANO Technologies, NANOSHEL, United Nanotechnologies Pvt. Ltd., NanoBio Chemicals India Pvt. Ltd., NanoFactor Materials Technologies, Qtech Nanosystems, Ogene Systems India (P) Ltd., Aisin Cosmos R&D Co. Ltd. are some major start-ups in nanotechnology materials and surface engineering in India. Among established companies, Mahindra & Mahindra Ltd., Tata Chemicals Innovation Centre, Hindustan Lever Research Centre, Jubilant Organosys Ltd., Auto Fibre Craft, BHEL (Ceramic Business Unit), and GE India Technology Centre are the major players.

In the area of nanobiotechnology, the major industrial actors among start-ups are Velbionanotech, Nano Cutting Edge Technology Pvt. Ltd. (Nanocet), SSB Technology, and Biomix Network Ltd. Among established biotechnology companies that have ventured in the area of nano-bio interface, some of the major players are Panacea Biotech, Dabur Research Foundation, Bharat Biotech, and Lifecare Innovations Pvt. Ltd.

Nanoelectronics is another important application area in the nanotechnology industrial landscape in India. Bharat Electronics Ltd., Cranes Software International Ltd., and Samtel Color Ltd. are some important players in this arena. Though the Indian semiconductor and hardware industry is characterized by a poor electronics manufacturing base and the absence of chip-making facility, the need for investment in nanotechnology R&D in the semiconductor industry to innovate diverse applications based on nanomaterials and nanotubes such as consumer goods, including mobile, laptops and tablets, medical equipment, energy efficiency, and security, has been felt and emphasized upon (*The Times of India*, 2011).

Nanotechnology instrumentation being an important area requires massive investment from companies. For instance, Mp3SNanotechnology Pvt. Ltd. manufactures equipment for textile waste water recycling for dyeing and other processes.

The source of technology at the firm level is either technology developed through in-house R&D or, obtained/developed in collaboration with an external source, which may either be a publicly funded research institute or a privately owned research entity (Tables 2.1 and 2.3). This reflects the growing trend of public–private collaboration in the emerging areas of S&T. Also, a majority of the technologies that have been developed through PPP is in the interface area of nanobiotechnology.

Networks

For a tightly knit relationship between science, technology, and economic performance, partnerships and networking among producers and users of

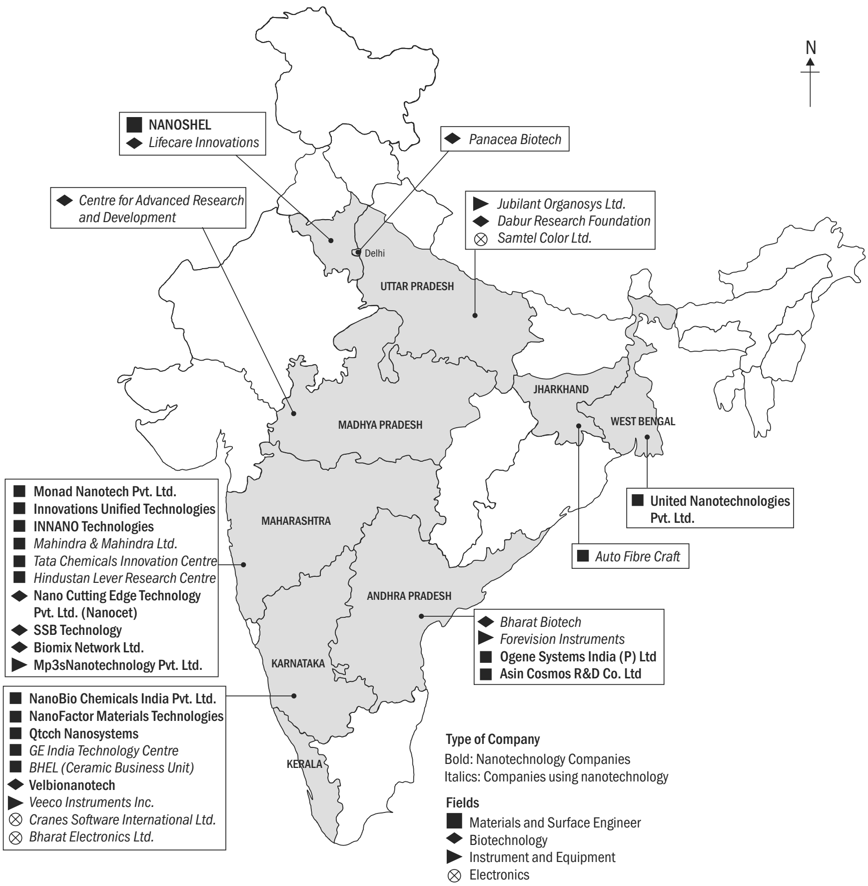

Figure 2.9: Nanotechnology industry in India
Source: Author's compilation

Table 2.1: Nanotechnology development through in-house R&D

Supplier/Manufacturer	Activity/Technology
Bhaskar Centre for Innovation and Scientific Research, Chennai	Antimicrobial spray (silver nanoparticles and herbal extracts)
University of Delhi, Delhi	A process of entrapping genetic materials in nanoparticles of inorganic compounds to form non-viral carriers
Virtus Techno Innovations, Mumbai	Gene repair therapy called Mitsanika and other bio-engineering applications using nanotechnology
Lifecare Innovations Pvt. Ltd., Gurgaon	Developed Fungisometm, a Liposomal Amphotericin B; nanotechnology-based novel drug delivery system for sustained release of anti-TB drugs
Velbionanotech, Bengaluru	Developed nanotech-based treatments for atherosclerosis (arterial plaque), nephrolithiasis (stone in the urinary tract), and diabetes
IIT-Bombay (Electrical Engineering Department)	Developed a cardiac diagnosis product iSens using nanotechnology that provides the reading of an individual's heart. Also, developed a silicon locket as a part of a complete suite for cardiac monitoring and diagnosis
Bilcare Ltd., Pune	Anti-counterfeit technology for drugs (nano-fingerprinting technology)

Source: Various sources

knowledge assume greater significance. In the context of nanotechnology, its knowledge intensiveness, interdisciplinary character, complexity of technology, uncertainty and associated risks, high cost of instrumentation, lack of requisite expertise, and an inability to capture adequate returns signifies the importance of collaboration and networking among various stakeholders.

All these have ramifications on how innovation in nanotechnology is carried out and diffused. Recently, there has been an increasing trend in the nanotechnology industry in India with the private sector beginning to invest in R&D laboratories at university and government institutions. Innovative mechanisms, such as incubators are supported by state-funding agencies to encourage the industry–academia–public R&D networking; for example, CranesSci MEMS (Micro-Electro-Mechanical Systems) Lab, located in the Department of Mechanical Engineering at Indian Institute of Science.

India's first Nano Park is being planned in Bangalore. Nanotechnology innovation parks are also being planned in the states of Gujarat and Himachal Pradesh in collaboration with Nanobiosym, a Boston-based company. The park to be established with PPP envisages the building up of innovation knowledge ecosystem which would scale up emerging and disruptive technologies such as the Gene-RADAR technology, a mobile phone like device that can be used for water testing, food safety testing, dialysis machines, catheters, and even advanced bio-fuels development in an affordable manner for developing country markets.

The NSTM of DST supports joint institution–industry linked projects and has promoted translational research to develop industrially relevant products and processes. Six collaborative projects have been developed so far with some financial assistance from the industry as well (Table 2.2). For application-oriented technology development, setting up of 'Nano Applications and Technological Development Centres' and 'Nanotechnology Business Incubators' has also been envisaged under the mission and it is planned to create a Research Industry Collaboration Hub (RICH) to promote M&A deals, collaborations, and investments in nanotechnology.

In the sectors in which nanotechnology has already found applications and products, the trend of collaboration/partnerships is already becoming visible. For example, in the health sector, there has been an increasing trend

Table 2.2: Institute–industry collaborations supported under the NSTM

Institute	Industry
Nano Functional Materials Centre, IIT-Madras	Murugappa Chettiar and Orchid Pharma
Nano Technology Centre, University of Hyderabad	Dr Reddy's Labs
Centre for Interactive and Smart Textiles, IIT-Delhi	ARCI, Hyderabad and Textile Industry
Centre for Pharmaceutical Nanotechnology, NIPER, Chandigarh	Pharma Industry
Rubber Nanocomposites, MG University, Kottayam	Apollo Tyres
Nanophosphor Application Centre, University of Allahabad	Nanotech Corp., USA

Source: http://nanomission.gov.in/

of collaboration, both among private organizations, and between public and private entities (See, Table 2.3 for some of the important collaborations in nanotechnology in the health sector in India).

Table 2.3: Collaborations in nanotechnology in health sector in India

Supplier/ Manufacturer	Activity/Technology	Source of Technology
Private–Public collaboration		
Dabur Pharma, New Delhi	Cancer drug Nanoxel (with nanopolymer base) and Docetaxel using nanotechnology drug delivery	Delhi University and Dabur Research Foundation
Panacea Biotech, New Delhi	Pharmaceutical formulation of non-steroidal anti-inflammatory drugs into polymeric micelles nanoparticles for ocular delivery in Nimesulide	University of Delhi
Shantha Biotechnics, Hyderabad	Process for preparing pharmaceutical formulation of Amphotericin B or other polyene antibiotics entrapped into nanoparticles of copolymeric micelles	University of Delhi
Transgene Biotek Ltd., Hyderabad	Drug delivery system for oral insulin (using bio degradable polymeric nanoparticles loaded with human insulin or hepatitis B surface antigen as a carrier)	IICT Hyderabad and Transgene Biotek Ltd.
Cadila Pharma, Ahmedabad	Nanosensor based typhoid detection kit (recombinant DNA technology and immunological technique for rapid detection)	IISc Bangalore (nanosensor), DRDE (typhoid detection kit)
Panacea Biotech, Chandigarh	Ophthalmic delivery using polymeric micelles nanoparticles	University of Delhi
Bharat Biotech, Hyderabad	Topical emulsion for oestrogen therapy (micellar nanoparticles technology) for drug delivery	Novavax, USA
Biocon, Bengaluru	Breast cancer nanodrug Abraxane (paclitaxel protein and albumin bound medicine).	Abraxis Biosciences, USA

Contd...

Table 2.3: Contd...

Supplier/ Manufacturer	Activity/Technology	Source of Technology
Nano Cutting Edge Technology (Nanocet), Mumbai	Biostabilized nanoparticles such as Ag, Au, Fe, Pd, etc., in the areas of cancer hyperthermia, targeted drug delivery, diagnostics, antimicrobial agents, and mitigation of pollutants	Agharkar Research Institute, Pune
Natco Pharma, Hyderabad	Nanotechnology drug, Albupax, which is used in the treatment of breast cancer. Albupax is the first generic version of the international brand Abraxane and consists of Paclitaxel in an Albumin-bound nanoparticle form.	Abraxis Bio-sciences, USA
Source: Various sources		

International collaborations in nanotechnology R&D are also gaining prominence in the various Indian S&T cooperation agreements. For instance, under the DST-NSF programme, joint R&D activities have been undertaken on carbon nanotubes, nano-encapsulating materials, etc. Similar collaborative work with several European countries is being pursued. A programme on engineered functional nanocomposites with a focus on magnetic properties, magnetic interactions, and gas-solid interactions, etc., has been initiated in collaboration with Germany. Growing trends of collaboration with Asian countries such as Japan, Korea, and China have also been witnessed in recent years.

Although there are no umbrella industrial organizations for the nanotechnology industry in India, but platforms such as the Nano Science and Technology Consortium (NSTC) provide an opportunity to industries, academics, and governments to forge partnerships and harness the potential of nanotechnology both at the global and national level. A number of established actors are already linked to the consortium and a number of international organizations are its strategic partners. Nanoscience Innovation Pvt. Ltd (Singapore), nDure Technologies Pvt. Ltd. (Australia), National NANOFAB CENTER (Korea), Midas System (Korea), CINVESTAV (Mexico), and Mezhregionsservis Ltd. (Russia) are amongst them. The Consortium has forged international tie-ups in commercializing the fuel-born catalyst in the global market, for commercialization of applications of nanosilver technology for companies working in the health and cosmetic sector, and providing material and technology for manufacturing of bullet-proof jackets/vests. There are also regional networks promoting transnational cooperation on nanotechnology research and education. Asian Nanoscience and Nanotechnology Association (ANNA) in Japan is one amongst them having an ANNA Chapter on India.

ICPCNanonet, a web network created under an EU-funded project, provides a platform for knowledge sharing and forging collaborations between scientists in the EU and the International Cooperation Partner Countries (ICPC) of China, India, Russia, and Africa. The network provides open access to an electronic archive of published research in nanotechnology (Nano Archive) and organizes webinars on topics concerning nanotechnology.

There also exists South–South Cooperation on nanotechnology. The IBSA Nanotechnology Initiative launched jointly by the partnering nations of India, Brazil, and South Africa envisages formulation of a mega-collaborative programme in areas of mutual interests like advanced materials, energy systems, sensors, catalysis, health (TB, malaria, and HIV), water treatment, agriculture, and environment.

In addition, industry associations such as the Confederation of Indian Industry (CII), Federation of Indian Chambers of Commerce and Industry (FICCI), Associated Chambers of Commerce and Industry (ASSOCHAM), Society for Indian Automobile Associations (SIAM), and Automotive Component Manufacturers Association (ACMA) have recognized the potential of this technology in meeting the economic and development needs of the country and have accordingly started playing important role as an industry-interface organization.

Institutions and policies

A different set of supporting institutions are needed for technologies that are temporally separated (Freeman and Perez, 1988; Freeman and Louca, 2001). It is now readily well-established that with the advent of any new technology, countries that have the basis of supporting institutions already in place for these technologies — or that can efficiently develop new institutions without much time lag — are usually successful in reaping benefits in a responsible way. Having said that, it would be worth discussing briefly the various institutions that have directly or indirectly influenced the trajectory of nanotechnology development in India. Institutions influencing nanotechnology can be viewed at two different levels — one concerning the background preconditions that facilitate technology development in general and the other which is technology or industry specific. We believe that a brief discussion about the institutions influencing S&T development in general would be important from the perspective that the existence of this set of institutions within a particular geographical setting has influenced or is influencing to a large extent the pace and direction of nanotechnology. It would also help ascertain whether the background preconditions were all set so that this emerging technology could pave its way into the Indian landscape.

The institutional environment in the first four decades of Indian independence favoured the building of indigenous technological capabilities. The policy of self-reliance and import substitution and allowing foreign transnational corporations only to invest, import, etc., resulted in adaptation of imported technology, thus enhancing indigenous technological capabilities. However, it is often said that the protectionist policy and inter-departmental turf led to India missing the semiconductor revolution in the 1970s (Khandelwal, 1981). This also resulted in a lack of interaction between the industry and R&D-performing institutions, and with the state being the sole sponsor of the scientific research, it was observed that the universities and national research centres mostly worked in isolation. This further put a constraint on developing a long-term vision for research-driven product or technology development. With the policy of liberalization and the announcement of the S&T Policy in 2003, the S&T landscape in India witnessed changes in the institutional environment. It was around this time that nanotechnology started garnering attention worldwide and India too planned to jump into the nanotechnology bandwagon. However, the complexity and nuances of this emerging technology, as discussed previously, necessitated institutional change and it is in this context that it becomes important to understand how institutions have evolved and shaped the trajectory of nanotechnology in India.

It could be said that a pre-existing base in the basic sciences facilitated an engagement with nanotechnology, which basically derives its strength from research in the basic sciences. As discussed earlier, in the NSTI an emphasis was laid on developing basic research in nanosciences. As a result, India developed a relatively strong base in fundamental research in nanotechnology and a wide breadth of materials has been covered making the magnitude of research being undertaken in this sphere large. However, the need for applied research and technology development was felt and addressed in the NSTM.

Also, a change in the way research is conducted in universities and R&D institutes could be observed with the advent of nanotechnology in the Indian landscape. Research at the interface of life sciences, medicine, physics, chemistry, material sciences, and engineering sciences has begun and specific emphasis has been placed on multidisciplinary research under the NSTM. Besides DST, other government S&T establishments have also underscored the need for undertaking multidisciplinary and interdisciplinary research in nanotechnology. Research in nanotechnology supported by DBT and DIT substantiate the beginning of interdisciplinary research. Also, the network project on nanomaterials and nanodevices in health and disease headed by CCMB involves 18 other CSIR laboratories possessing varying competencies.

Greater collaboration among industry, R&D performing institutions and government is being envisaged under the NSTM, which may play an important role in accelerating the development of nanotechnology from idea to market.

2.6 Dynamics of the Emerging Nanotechnology Innovation System

It would be too early to say that there exist innovation systems for nanotechnology in India. Figure 2.10 provides an overview of actors in the nanotechnology innovation landscape of India. Nanotechnology activity in India at the industry level is at a relatively lower level and there is a concentration of nanotechnology-related products in only few sectors, such as health. However, the research and experimental development activity in this emerging domain is diverse and a relatively strong knowledge base is evolving. Also, a lot of emphasis is being put on translational research and forging partnerships between industry, academia, and government. One could say that it is the 'innovation ecology' (Metcalfe and Ramlogan, 2005) (constituting various actors who are the repositories, generators, and users of knowledge that have begun to emerge prominently in the Indian nanotechnology landscape) and the 'system-making' connections (Metcalfe and Ramlogan, 2005) between the actors ensuring building up of knowledge and innovation capability though information flow that is generally weak albeit emerging in certain economic sectors (Figure 2.11).

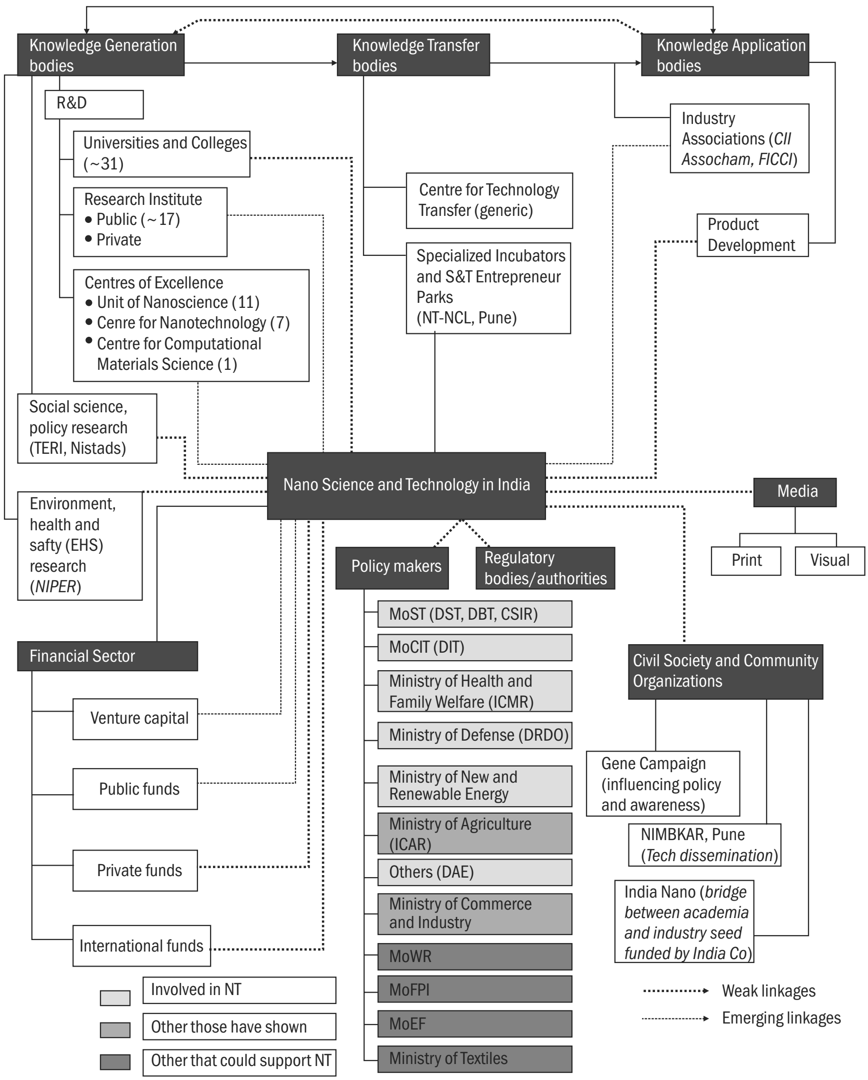

Figure 2.10: Nanotechnology stakeholders in India
Note: Figures in parentheses indicate the numbers

In the previous section, we have attempted to map these innovation ecologies of nanotechnology in India and tried to track the channels/ways through which actors are connected and knowledge sharing is taking place. Section 2.6 discusses the dynamics of innovation ecology and system-

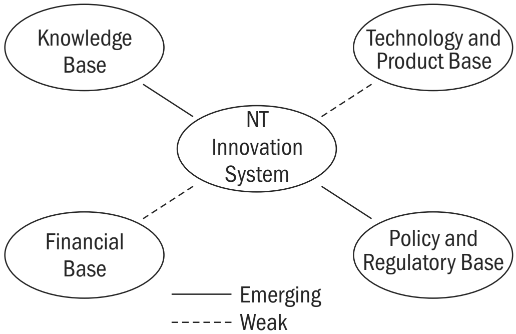

Figure 2.11: Innovation ecology and system-making in nanotechnology in India

making in nanotechnology in India and explores various policy instruments that might create opportunities and innovation capability building by stimulating innovation system formation (Metcalfe, 1995, 2004; Smits and Kuhlmann, 2004).

2.6.1 A relatively strong knowledge base but need for transdisciplinary research and technology development and commercialization

The desire to utilize nanotechnology as a tool to facilitate socio-economic development necessitates the development of products and applications and their commercialization. This not only demands emphasis on basic and applied research, but also on technology development, efforts towards commercialization, and developing inter-linkages and partnerships amongst the actors in these various domains. Since nanoscience might feed into several existing technologies, it also necessitates interdisciplinary research. India has however known to have fallen short on several of these fronts. For instance, the private sector participation in gross domestic expenditure on R&D though has increased in recent years, but still remains at 28 per cent (*UNESCO Science Report*, 2010).

India has been known to traditionally favour basic and theoretical sciences over technology development. It has been argued that while basic sciences is India's forte, we lack quality expertise in engineering as well as product development and also lack efficient mechanisms that enable the transfer of research and knowledge from the lab to market (Srivastava, 2008). Also, translational research that has the capacity to be taken from the laboratory to industry is lacking probably due to the traditional emphasis on publications in the Indian S&T system rather than applications development. Additionally, the environment for PPP and industry participation in public-funded research is also perceived as being under developed when compared to the developed countries. These gaps intrinsic to the Indian S&T system have also seen to ail the nanotechnology domain, especially in its early years. Aside from these gaps, technology development in the nanodomain brings along with it, its own unique challenges of being cost intensive with long gestation periods as well as in several cases having to be merged with engineering, applications or devices in other domains. Added to this is the fact that barring a few instances, Small and Medium Enterprises (SMEs) and start-ups are non-existent in the nanotechnology scenario and venture capital is virtually non-existent. Therefore, India is much behind other developed and developing countries, such as China and Korea in this sphere. Thus, though encouraging signs of product development, industry participation, and PPPs in nano S&T appear to dot the nanotechnology landscape, technology development, for all of the above reasons, will assume significant challenges in the Indian context. As India completes nearly a decade of full-fledged engagement with nano S&T, there is a vital need to energize the capacity-building processes that enables rapid and efficient application development by devising strategies that engage all relevant stakeholders from the conception of the research.

Recently, the government announced new policy measures to encourage the 'development and commercialization of inventions and innovations'.[1] They include allowing researchers working in public academic and research institutions to also hold equity in spin off companies and enterprises and also facilitating mobility of researchers between academic institutions and industry. The former initiative would enable new avenues for the translation of innovative lab research into commercial applications and technology that was previously undertaken by private companies that are usually risk averse. This new initiative would encourage scientific entrepreneurship and allow scientists with promising research in the nanodomain as well as the expertise to create start-ups and aim for applications development. As nanotechnology is a cost-intensive endeavour, scientists could leverage the facilities, infrastructure, and manpower already developed at their centres

[1] See, http://dst.gov.in/

to undertake technology development ventures in nanotechnology. On the other hand, the exchange of personnel amongst academic institutions and industry will help the transfer of expertise and skills to bring forth new ideas and knowledge for application development in this area. The understanding of the concerns and perspectives on both sides would enable successful PPPs and technology development, both of which are proving to be a major challenge in the nanotechnology arena.

2.6.2 Nanotechnology 'applications overload': Need for a clear understanding of priorities, focus areas, and capabilities

Alvin Toffler, in his book *The Future Shock,* popularized the concept of 'information overload' to suggest the difficulty that a human being may face, caused by the presence of too much information and a rapid rate at which new information is being produced. A parallel to this may be drawn in the rapidly emerging domain of nanotechnology in terms of its innumerable applications in different economic sectors or what we call 'applications overload'. In this regard, academics, corporates, and policy-makers have to make judicious decisions in prioritizing and supporting any particular application area. Nano-related R&D has since its jumpstart in 2001 come quite a long way in India. As observed, several initiatives are underway and in the pipeline. Also, many areas have been supported by diverse agencies in the R&D context. Therefore, at this juncture, it would be appropriate to investigate the area in which India has developed expertise as well as any areas that it has engaged in to some extent but might want to develop competence in for various reasons. An understanding of the international R&D scenario might also be undertaken to locate any more new areas of potential research that might be significant in the Indian context or addresses any of our socio-economic needs. If core areas of R&D interest that have been identified include broad sectors such as energy, water, health and agriculture, and the like, sectoral road maps might also be evolved for each as has been done in some other countries. Also, a clear understanding of the existing capabilities and the ways to build capabilities in the identified focus areas would be essential in this regard, as discussed in Chapter 8.

A technology foresight mechanism might be utilized for identification of R&D priorities. Through this exercise, apart from surveying research interests, a stock of all the institutions, infrastructure, facilities, and human resources as well as collaborations developed since the year 2000 might be undertaken to get a detailed understanding of what has been accomplished and what gaps remain. These surveys together might allow us to develop more coherently the core areas that we might want to emphasize while building R&D capacity and prevent diffuse efforts and fragmentation of resources. Added to this, several experts — policy-makers from various agencies, scientists, industry that has been engaging in nanotechnology — might be approached for opinions on several of the issues. Developing a roadmap might also provide an opportunity to help address the issue of developing coordination amongst all the agencies involved in the nanotechnology R&D policy-making scenario. A preliminary survey on the status of nanotechnology in India has been conducted by the National Foundation of Indian Engineers and supported by MoST through the National Science and Technology Management Information System (NSTMIS). Information from this may be used to develop a broader road map that takes into consideration more dimensions.

An initial broad framework with guidelines on issues to be addressed might help develop a more detailed strategy. A national advisory committee had been previously set up to guide R&D in the nanotechnology domain. They have, for example, deliberated at the national review and coordination meeting on nanotechnology. The composition of committee members reveals that apart from scientists, policy makers from selected R&D agencies such as the DST and DRDO are also involved. The Department of Atomic Energy (DAE) and CSIR represented by scientists from laboratories or centres within these organizations, have been included. However, industry has just one representative.

Multi-stakeholder engagement with S&T issues and decisions in India is rare and usually the prerogative of the policy and scientific research community. The nanotechnology trajectory in India has also largely been shaped by policy makers. However, in the nano S&T context, there is much to gain from engaging multiple stakeholders. For example, since nanotechnology requires cost-intensive development, professionals might help identify priority areas that nanotechnology might address, risk professionals might help develop strategies for risk management, etc. Policy makers from other agencies such as the Planning Commission and Ministry of Commerce as well as industry associations like the CII and FICCI — who are also leading industry engagement in nanotechnology in India — might be involved. This approach would help identify and explore the benefits, challenges, and risks this technology poses to India and strategize to channel its potential in a sustainable manner, for national benefit. On the other hand, India while developing its national strategy might also draw from existing strategies of developed countries. However, caution must prevail on this front and in the use of this approach as contexts, priorities, and needs of a developing and diverse country like ours could be very different to other developed or even developing country counterparts, especially in areas as mentioned above.

Scientists have acknowledged that a degree of overlap exists in the context of support for R&D amongst various funding agencies. It has been suggested that this occurs because these agencies, especially those that are situated in different ministries (e.g., DBT, ICMR, DRDO), appear to be functioning independently. This scenario it appears has spilled over into the nano S&T arena as well and might lead to a problem unless it is addressed effectively. In fact, it was observed that projects that were sanctioned via NSTI/NSTM as well as SERC, both falling under the umbrella of DST, had once again similar R&D themes such as health, energy, etc.

While some experts believe that jurisdiction overlaps in the R&D context has not posed a major problem[2] or led to any significant waste of resources, several others have felt that this overlap in R&D jurisdictions has hampered Indian S&T to an extent. In fact, recognizing this issue as an intrinsic problem and to avoid 'carbon copy' research, an initiative has been undertaken by DBT to develop a database that incorporates information on projects that it has sanctioned which it is hoped will be available to all agencies. It is unclear if this database also contains lists of projects supported by other agencies. In another example, in an effort to develop focus in R&D funding, it was felt that DRDO needed to focus on 'core and critical areas' of R&D as it has been engaging in research across several areas

[2] Experts here argue that each agency has a different 'approach' to supporting research in what might be similar areas of R&D. While DST funds research in life sciences, it does so at a smaller scale while DBT's approach has been to develop large networked projects with specific scientific deliverables. The latter also focuses on developing applications for industries and commercialization of technologies. The ICMR, on the other hand, supports R&D that is of greater significance for public health which might make the basis for its research slightly different from that of the DBT. The DRDO might concentrate on defence-related R&D.

ranging from missiles, radars and electronic warfare programmes to even juices, mosquito repellents, and titanium dental implants.

In the context of nanotechnology, common areas of interest amongst funding agencies might allow for unrestricted and assorted nano S&T R&D dimensions to be addressed across the spectrum of areas. Yet however it might lead to various pitfalls. Support to duplicative research, a major consequence that might arise from such a situation, might lead to a strain on the already constrained financial resources of the nanotechnology budget if not the Indian S&T budget, especially since building capacity in nano S&T is cost intensive. This would also lead to a waste of human resource efforts as similar research undertaken by different scientists would be supported. Since R&D involving development of nanomaterials, as well as health and energy, is witnessing multiple agency engagement and duplication of R&D, it poses a real threat to scientific resources. Multiple agency engagement with R&D in a particular area might also contribute to an ambiguity in identifying an agency to take on responsibility for developing and implementing sector-specific strategy in nanotechnology as well as an uncertainty amongst researchers as to which agency to approach for funding specific projects.

2.6.3 Co-evolving physical and social technologies for economic growth and development: What are the needed institutions?

While referring to a technology, attention is focused mostly on the 'physical' technology — the actual technological artefact and there is a scant attention on 'social' technologies — i.e., set of actions or procedures needed to perform an economic activity and the way work is divided and coordinated to perform that activity efficiently and productively (Nelson and Sampat, 2001; Nelson, 2008). Different structures and forces, denoted as 'institutions', such as laws, norms, governance structure, and customary practices tend to influence which social technologies will be employed in an economy. In this regard, to get a comprehensive hold on the processes that drive nanotechnology development, it would be important to have institutions which hold in place social technologies which in turn complement physical technologies. However, there is a caveat that social technologies develop much more erratically and slowly than do physical technologies as selection forces usually are significantly weaker for institutions and social technologies than for physical technologies (Nelson, 2008). Nature of business activity, academia–

industry linkages, prevailing patent regime, policies, and programmes are some of these.

The innovation system for nanotechnology at the moment is still characterized by a focus on upstream governance measures with an emphasis on support for research and knowledge accumulation, developing the skill base and research infrastructure. Moreover, these activities are being promoted at a more generic level without focusing on any particular sector or area of application, in contrast to countries such as China which has clear strategies and focus areas of applications. With the arrival of certain nanotechnology products in the Indian market, there is a plan to formulate a Nanotechnology Regulatory Board with an aim to regulate nanotechnology-based industrial products. However, little emphasis has been laid on downstream governance apparatus concerning environmental and health implications of nanotechnology, procurement, regulations, and standards in this domain. These aspects have been somewhat dealt in detail in Chapters 4 and 7, respectively.

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CHAPTER 3

Nanotechnology Developments and Applications in Energy and Environment Sectors

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3.1 Introduction

Energy security combined with concerns of climate change has led to increased research in the area of sustainable energy sources. Nanotechnology has the potential to contribute at several levels towards achieving this. Substitution of conventional materials with nanomaterials has led to improved performances and lesser material requirements (e.g., fuel cell catalyst[1]). In some cases, use of nanoformulations has led to alternate simpler processes thereby reducing the cost; e.g., nanoparticle ink for printing thin film solar cells (Cho et al., 2012). It can also contribute to improved safety; e.g., replacement of reactive graphite in lithium ion battery (Jiang et al., 2011).

The potential of nanotechnology in the energy sector has been described across the entire value chain covering energy generation, energy distribution, energy storage, and energy usage.[2] Its potential arises from unique electrical,

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[1] Understanding Nanotechnology, http://www.understandingnano.com/fuel-cells.html, (last accessed: March 2012).

[2] Hessian Ministry of Economy, Transport, Urban and Regional Development, http://www.hessen-nanotech.de/mm/NanoEnergy_web.pdf, (last accessed: March 2012).

magnetic, and mechanical properties due to nanodimensions.[3] Nanomaterials are being used to improve efficiency of existing energy technologies and also improve commercial viability of new energy technologies.[4] However, issues such as replicating laboratory performances at the manufacturing level, safety and risk aspects, end of life product recovery or recycle or disposal and net lifecycle energy, and cost advantages need to be examined further. In this chapter, the use of nanotechnology in the energy sector, particularly in energy generation and storage is covered. Sources of information are recent patents, technology transfer, and commercial activities covering clean energy products including energy storage devices. The status of technology for use of nanomaterials in fuel cells, solar energy, hydrogen storage, lithium ion batteries, and capacitors is described in this chapter.

The use of nanotechnology for environmental applications covers its applications in water and wastewater treatment, air clean up, and sensors. A variety of materials such as adsorbents, membranes, catalysts, and composites incorporating nanomaterials or nanopores have been used. They offer better efficiency, selectivity, and performance under less stringent conditions (e.g., room temperature activity in case of nanocatalysts).

Though some nanomaterials for environmental applications are available commercially, their application presently is mostly at the research stage only. One of the reasons for this is the fact that often ecological and health risks in these applications are not fully understood. The status of the technology in water and wastewater treatment, air pollution control, and sensors is described in this chapter covering primarily research activities.

3.2 Nanomaterials in Energy Applications

3.2.1 Fuel cells

Fuel cells generate electricity electrochemically using hydrogen as the fuel. There are different types of fuel cells based on the operating temperature and materials used. The ones that have reached near commercialization stage are polymer electrolyte membrane fuel cell (PEMFC) for low temperature applications and solid oxide fuel cells (SOFC) for high temperature applications.

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[3] NanoConsulting Pte. Ltd., http://www.nanoconsulting.com.sg/doc/SingNanoEnergy2010.pdf, (last accessed: March 2012).

[4] United States National Nanotechnology Initiative, http://www.nano.gov/you/nanotechnology-benefits, (last accessed: May 2013).

Nanotechnology is used in many components of fuel cells. This includes catalyst, membranes, hydrogen generation materials, etc. Low temperature fuel cells have several nanocomponents to improve performance, extend life or reduce costs. Some companies are developing products for fuel cells based on nanomaterials. Advanced membrane electrode assembly and nano palladium catalyst are now available which lead to a higher power output and lower cost.[5] Electrodes based on carbon nanotubes have been developed for low temperature fuel cells, particularly methanol fuel cells. The performance of these electrodes was found to be superior to other commercially available electrodes.[6] Nanocatalyst coated electrode has been developed for electrolysis that offers high efficiency and high rate for water electrolysis.[7] Nano-based photocatalysts have been developed which can improve efficiency and reduce electricity required to generate hydrogen from water.[8] Commercialization of a gold-Pt catalyst has been reported for low temperature fuel cells which are supposed to be cheaper, more efficient, better CO tolerant, and containing lower amount of precious metal catalyst.[9] A recent article (Doe, 2008) has examined the use of nanomaterials in commercial products, particularly portable fuel cells. As described in the article, commercial direct methanol fuel cells (DMFCs) are available on the basis of nanocatalyst and nano-based membrane electrode assembly. The manufacturer reports higher efficiency compared to previous generation models. The article also mentions that a novel nanocatalyst has been used in 20 Wh fuel cells based on sodium borohydride and alcohol fuel. Nanochannels in the membrane assembly have been used to regulate the flow of fluids, thus reducing the methanol crossover and water management requirements. Similarly, another company has used a nanoengineered combination of hydrophilic and hydrophobic layers in the membrane assembly to eliminate external pumps and controls for water recirculation.

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[5] QuantumSphere Inc., http://www.qsinano.com/white_papers/2008_07_03_dmfc.pdf, (last accessed: May 2013).

[6] Unidym, Inc., http://www.u nidym.com/products/fuelcell.html, (last accessed: March 2012).

[7] Gridshift Incorporated, http://www.grid-shift.com/white_papers/docs/On_Demand_2_pager.pdf, (last accessed: March 2012).

[8] Nanoptek Corp., http://nanoptek.com/, (last accessed: March 2012).

[9] Blue Nano, http://www.bluenanoinc.com/products/chemical-fuel-cell-catalyst-technology.html, (last accessed: March 2012).

At the research level, many configurations of nanocarbon are being examined for low temperature fuel cells. These include carbon nanotubes grown on carbon nanofibres with catalyst loading, carbon nanotubes grown on carbon paper for PEMFC electrode, aligned carbon nanotube, carbon nanotube membrane, carbon nanohorns, ordered nanoporous carbon, etc. In recent works, nitrogen doped carbon nanotubes have been developed for improving the performance and reducing the precious metal catalyst requirement for fuel cell catalyst (Shao et al., 2008). Development of carbon nanosphere coated with platinum nanowires has been reported and it showed improved performance for oxygen reduction reactions (Sun et al., 2008). A titanium tungsten oxide support for platinum nanocatalyst with improved CO tolerance has also been reported (Wang et al., 2010a). A catalyst comprising a palladium core surrounded by an iron-platinum (FePt) shell has been reported. This catalyst generated more current than other platinum-based catalysts (Mazumder et al., 2010). In another development, a sub nano platinum catalyst was prepared using a dendritic phenylazomethine template to which platinum chloride was added. The smallest particle that could be obtained comprised 12 atoms.[10] There are also instances of industry-led research such as the Nano-Engineered Catalyst Layers and Sub-Structures (NECLASS) project for developing nano-based membrane electrode assembly.[11] To increase life of Pt catalyst, particularly in automobile applications where voltage changes are likely to be encountered, researchers have developed a new configuration of catalyst. The catalyst is made of a palladium core on which a single layer of catalyst is coated. The catalyst showed good reactivity and stability.[12] In a recent patent, nano palladium has been used as a catalyst for a direct organic fuel cell using formic acid liquid fuel which is expected to overcome some problems of organic fuel cells such as low power density, CO poisoning of catalyst, etc.[13]

Other nanocomponents are also being researched or manufactured. Nanocomposite sealants have been developed by the American Engineering

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[10] Chemistry World, http://www.rsc.org/chemistryworld/News/2009/July/20070902.asp, (last accessed: March 2012).

[11] NECLASS Project, http://www.nanotech-now.com/news.cgi?story_id=37132, (last accessed: March 2012).

[12] Brookhaven National Laboratory, http://www.eurekalert.org/pub_releases/2010-11/dnl-nhs111010.php, (last accessed: March 2012).

[13] Masel RI, Y Zhu, RT Larsen, 2010. "Palladium-based electrocatalysts and fuel cells employing such electrocatalysts", US Patent 7785728.

Group for fuel cell applications.[14] Nano-porous Solutions Limited have developed and commercialized adsorbent hollow fibres which has application as PEMFC humidifier.[15]

In case of SOFCs, there are many companies reporting either on the manufacture of SOFCs or on SOFC components with nanomaterials (Blum et al., 2005). However, the use of nanotechnology in these products is not explicitly mentioned. There are several patenting activities from industries, research organizations, and academic organizations. These cover electrodes, interconnects and electrolytes targeting improved performance, stability, conductivity, lower temperature operation, and reduced amount of catalyst. These are described in the following paragraphs.

Room temperature SOFCs using nano zirconia and ceria doped with yttria and samaria has been developed and a patent has been filed.[16] One company has unveiled an SOFC prototype for automobile application based on nanotechnology.[17] A patent application has been filed for nano yttria containing chromium alloy for use as interconnect in SOFCs.[18] Use of nanotechnology in reversible SOFC has been patented. The electrodes in this SOFC are formed by impregnation of the sintered precursor layer leading to formation of nanocatalysts which not only improves the performance but also leads to reduced catalyst requirement.[19]

There are several patents on anodes for SOFC. Nano yttrium-doped strontium titanate (SYT) powders have been used for preparing porous anode using thermal spray technique for intermediate temperature SOFCs.[20] A

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14 American Engineering Group, http://www.engineering-group.com/papers/aeg_doublelipfuelcell.pdf, (last accessed: March 2012).

15 Nano-porous Solutions Ltd., http://www.n-psl.com/, (last accessed: March 2012).

16 PROvendis GmbH. Available at http://www.lifescienceslink.org/profile/feedback/1559/nanox-sofc-room-temperature-fuel-cell/en. (last accessed: May 2013).

17 https://www.visitcars.co.uk/car-blogs/AUTOinCAR/Nissan Prototypes Fuel Cell for Automobiles with Nano Technology/159165/, (last accessed: May 2013).

18 Sarma S S and R Sundaresan, 2009. "Processing of powders of a refractory metal based alloy for high densification", US Patent No. 20090068055.

19 Larsen PH, 2009. "Method for producing a reversible solid oxide fuel cell", US Patent No. 7601183.

20 US Nanocorp, Inc., http://www.usnanocorp.com/sofc.htm, (last accessed: March 2012).

method for preparing anodes with nano gas channels using plasma spraying has been reported which led to increase in electrochemical activity.[21] Composite nanoparticles produced by direct deposition or flame spray pyrolysis has been patented for use as SOFC anodes to improve stability and electrochemical activity.[22] Nano ceria based anodes have been obtained by solution impregnation on a doped strontium titanate backbone which led to high electrochemical activity at a wider range of temperatures.[23]

There are also patents on cathodes and electrolytes. A nanospray combustion processing technology has been developed for making thin film samaria doped ceria (SDC) electrolytes which can operate at a lower temperature of 700 °C.[24] A method for preparing SOFC electrolyte from nano-scale electrolyte powders using spin coating has been described in a patent.[25] Nano thin film electrolyte with a silicon support has been described.[26] Nanoporous cathode by using pore forming agents to increase the reaction area has been reported.[27] A cathode containing nanocatalysts on or close to a triple phase boundary to improve efficiency has been described.[28] With a view towards making cheap and robust SOFCs, a patent describes the SOFC structure which also contains nanocatalysts.[29]

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21 Changsing H, 2011. "Nanostructured composite anode with nano gas channels and atmosphere plasma spray manufacturing method thereof", US Patent No. 8,053,142.

22 Ehrman SH, RK Pati, and O Akhuemonkhan, 2010. Solid oxide fuel cell (SOFC) anode materials, US Patent No. 7,842,200.

23 Blenow P, M Mogensen, and HK Kammer, 2010. "Ceria and strontium titanate based electrodes", European Patent No. EP2254180 (A1).

24 nGimat Co., http://www.ngimat.com/index.html, (last accessed: March 2012).

25 Chang YC, MC Lee, CH Wang, TN Lin, and WX Kao, March 2010. "The formulation of nano-scale electrolyte suspensions and its application process for fabrication of solid oxide fuel cell-membrane electrode assembly (SOFC-MEA)", European Patent Application No. 20100018036.

26 Hong H, S Pei-Chen, BP Friedrich, JF Rainer, and S Yuji. "Design and fabrication method of thin film solid oxide fuel cells", US Patent Application No. WO2008US10069 20080822.

27 Lust E, G Nurk, P Moeller, I Kivi, S Kallip, A Jaenes, and H Kurig, 2010. "Method for the preparation of a solid oxide fuel cell single cell", European Patent No. EP2160785 (A1).

28 Ruud JA, KW Browall, TJ Rehg, S Renou, and T-M Striker, 2010. "Electrode structure and methods of making same", US Patent No. 7,691,770.

29 Blenow P, M Mogensen, and HK Kammer, "Ceria and strontium titanate based electrodes", US Patent Application No. EP2008001483720080821.

There are several research publications regarding the use of nanomaterials in SOFCs. Research is underway as part of a consortium group to develop nanocoatings based on cerium on the steel parts of the SOFC to reduce their degradation during the high temperature operating conditions.[30] Nano Y_2O_3 has been dispersed in two ferritic stainless steels by high energy ball milling which led to interconnects with high electrical conductivity and better matched thermal expansion coefficient (Ahn et al., 2008).

Thin film nano-scale yttria-stabilized zirconia (YSZ) electrolyte membrane has been prepared which gave good performance at a lower temperature of 500 °C (Tsuchiya et al., 2011). Nanostructured $(La,Sr)(Ga,Mg,Co)O_{3-\delta}$ electrolyte has been prepared by aerosol deposition for low temperature SOFCs (Choi et al., 2012). Nano-sized YSZ were prepared by hydrothermal method and could be used to form dense SOFC electrolyte by sintering at temperatures lower than 1000 °C which prevents contamination from NiO in the NiO-YSZ anode when the layers are co-sintered (Fan, 2011). Nano erbium stabilized bismuth oxide powders along with gadolinium-doped ceria have been used to prepare bilayer electrolyte by colloidal deposition process to obtain higher conductivity electrolyte for low temperature SOFC (Lee, 2012). Nanocomposite electrolytes based on $Gd\text{-}CeO_2\text{-}(LiNa)CO_3$ have been prepared and characterized for low temperature SOFC (Rajalekshmi and Basu, 2011).

SOFC anode made of nanostructured Ni-YSZ cermet was prepared by plasma spraying and showed high gas permeability, stable high temperature conductivity, and enhanced catalytic activity (Ansar et al., 2007). The steam reforming performance and its effect on nano Ni particle sintering was compared for $Ni\text{–}Ce_{0.75}Zr_{0.25}O_2$ (Ni-CZO) cermet anode and $Ni\text{-}Ce_{0.9}Gd_{0.1}O_2$ cermet anode and it was found that the sintering was less in case of Ni-CZO anode (Prasad et al., 2012). Nano electro-catalyst based on $PrBaCo_2O_{5+x}$ (PBC) was prepared by impregnation on a samaria doped ceria backbone and this gave high electrochemical activity (Wang et al., 2012). Nanocomposite powders of NiO/YSZ-YSZ have been used to prepare anode functional layer which led to higher power density (Myung et al., 2012). Post annealing treatment of Ni-YSZ nanocomposite thin film has also been studied with a view to prevent agglomeration of Ni (Noh et al., 2010).

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[30] Nordic Innovation, http://www.nordicinnovation.org/sv/projekt/nano-coatings-for-solid-oxide-fuels-cells-nacosofc/, (last accessed: March 2012).

Nano electrodes by solution impregnation or infiltration have received lots of attention and this has been the subject of a recent review. While they offer many improvements and advantages, their long-term stability under SOFC operating conditions need to be studied (Jiang, 2012). Cathode based on $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF) has been studied for intermediate SOFC and their preparation by sol gel method to obtain particles in the size range 60 to 120 nm has been reported (Moharil et al., 2012). Nano-sized $Sm_{0.5}Sr_{0.5}CoO_{3-\delta}$ (SSC) was used in SOFC cathode by ion impregnation method and gave good cell performance at intermediate temperatures (Zhang et al., 2011). Nanostructured $La_{1-x}Sr_xMnO_3$-YSZ composite porous cathodes have been prepared by aerosol deposition which could be carried out at temperatures below 500 °C (Choi et al., 2011a). Nanostructured $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$ has been prepared by using complexing with chelants and inorganic dispersing agents which helped in reducing the temperature needed for phase formation and for maintaining the nanostructure respectively and led to increase in cell performance by 60 per cent (Kim et al., 2011). To improve the low temperature ionic conductivity of SDC, nano SDC has been coated with a thin layer of LiZn-oxide (Wu et al., 2012a). To reduce the sintering temperature of doped ceria, nano gadolinium doped ceria has been prepared by co-precipitation and 97 per cent density could be obtained at 950 °C (Hari Prasad et al., 2010).

3.2.2 Solar energy

Solar cells convert solar energy directly into electricity by photovoltaic effect. Nanomaterials have been extensively studied for solar cell applications and nanotechnology-based solar cells have been developed by many companies. In the US particularly, several companies funded by venture capital and based on close collaborations with universities or national labs have emerged. Silicon solar cells are the dominant ones in the market. Second generation solar cells such as thin film solar cells would have the advantages of flexibility and lower cost. Third generation solar cells have the advantages of higher efficiency, and include organic solar cells, dye sensitized solar cells. Nanomaterials are being used in many of these solar cells for performance improvement, cost reduction, ease of assembly, etc. These developments are summarized in the following paragraphs.

The pioneer of the thin film technology is a company which developed the process for printing CIGS (Copper, Indium, Gallium, Selenium) cells using nanoparticle ink.[31] Nanoparticle-based ink has also been used by another company to print CIGS solar cells. This technique offers faster production and minimizes expensive vacuum systems, typically needed for silicon solar cells. The efficiencies are expected to become competitive with that of silicon solar cells.[32] CIGS-based thin film technology is also being used by another company for their solar cells. Thin film CIGS are also being made using an ion beam assisted process for deposition on substrates.[33] Manufacturing process for nano CdTe ultrathin film solar cells has been developed.[34] Work is also in progress on pulsed plasma deposition for CdTe thin films solar cells (Nozar et al., 2011). Manufacturing facilities have also been set up for thin film copper indium selenide (CIS) solar cells; however, some of the activities are being sold to other companies.[35] One company has licensed liquid phase deposition technique from a university for developing thin film solar cells and envisage the use of this technology for making tandem solar cells.[36]

Third generation organic photovoltaic cells which have fullerenes deposited on a polymer is being examined by a company.[37] Transparent coatings on glass based on organic photovoltaics containing fullerene derived polymers, is being marketed. Another third generation solar cell technology being developed is based on thin film quantum dots prepared by screen printing or inkjet processes which are low cost and simple.[38] Triple junction multiple quantum well device has been developed which improves conversion efficiency.[39] One company has developed solar brush made up of

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[31] International Solar Electric Technology, Inc., http://isetinc.com/index.php, (last accessed: March 2012).

[32] Nanosolar, Inc., http://www.nanosolar.com/ (last accessed: March 2012).

[33] Solarion AG, http://www.solarion.net/start-en/r-start-en.html, (last accessed: March 2012).

[34] Solexant Corp., http://www.solexant.com/Series_C_Pilot_Line_Press%20Release_FINAL.PDF, (last accessed: March 2012).

[35] Würth Solar GmbH & Co. KG, http://www.wuerth-solar.de/solar/en/wuerth_solar/home_3/Solar_Startseite_neu_aktiv_1.php, (last accessed: May 2013).

[36] Natcore Technology, http://www.natcoresolar.com/, (last accessed: March 2012).

[37] Nanowerk, http://www.nanowerk.com/news/newsid=23139.php,(last accessed: March 2012).

[38] Solterra Renewable Technologies, Inc., Available at http://www.solterrasolarcells.com/product_innovations.php?ID=3, (last accessed: March 2012).

[39] JDS Uniphase Corporation, http://www.jdsu.com/go/quantasol/Pages/default.aspx, (last accessed: March 2012).

nano solar cells in the form of bristles.[40] Tunable nano silicon in the form of nanowires for high efficiency solar cells is being developed.[41] Also, another third generation technology is the dye sensitized solar cell based on the principles of photosynthesis. The electron emitted by the dye on exposure to sunlight is absorbed by nano titania. The technology has been licensed and commercial products are underway.[42] Based on the same technology but using natural pigment, solar cell kits for educational and other purposes are available.[43] Some companies are also offering dye sensitized solar cell components.[44]

Many patents have been filed pertaining to the use of nanomaterials in solar cells. For silicon solar cells, this includes silicon nanowires,[45] nano/microsphere lithography to improve efficiency of low-cost silicon solar cells,[46] nanoparticle silicon carrier emitters to improve efficiency,[47] and silicon nanowire with metal nanoclusters for improved electrical and optical properties.[48] Aluminium paste containing nanometals has been developed for use in silicon solar cells to improve conversion efficiency[49] and the aluminium paste comprising aluminium powders of different size and shape, including nanopowders, has also been patented.[50] Other nanomaterials that have been patented include TiO_2-multi-walled carbon

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40 Bloo Solar, Inc., http://www.bloosolar.com/, (last accessed: March 2012).

41 Bandgap Engineering, Inc., http://www.bandgap.com/index.html, (last accessed: March 2012).

42 Dyesol, http://www.dyesol.com/partners/current-projects, (last accessed: May 2013).

43 Man Solar, http://www.mansolar.nl/, (last accessed: March 2012).

44 Solaronix SA, http://www.solaronix.com/, (last accessed: March 2012).

45 Hwan JC, JM Sung, KJ Hyeok, KH Ju, and LS Ho, Method for manufacturing silicon nano-wire, solar cell including the same, and method for manufacturing the solar cell, European Patent Application No. JP20090245621 20091026.

46 Graham W, S Guha, O Gunawam, GS Tulevski, K Wang, and Y Zhang, 2010. "Nano/Microwire Solar Cell Fabricated by Nano/Microsphere Lithography", International Patent No. WO2010144274 (A1).

47 Swanson, RM, 2010. "Solar cell having silicon nano-particle emitter", United States (US) Patent No. 7705237.

48 Park GS, IY Song, S Heo, DW Kwak, HY Cho, HS Kim, J-M Choi, MS Kwon, 2011. "Silicon nanowire comprising high density metal nanoclusters and method of preparing the same", European Patent No. EP 2372751.

49 Wu CM, CL Chao, YC Lu, and WJ Huang, "Conductive aluminum paste and the fabrication method thereof, the solar cell and the module thereof", Patent Application No. EP20110154145 20110211.

50 Lee IJ, JG Park, JP Eom, and SG Kim, "Paste and solar cell using the same", Patent Application No. WO2010KR02132 20100407.

nanotube (MWCNT) nanocomposite for improved efficiency of dye sensitized solar cells,[51] electrically conducting films containing quantum dot absorbers,[52] organic solar cell with nano diamond and fullerene containing layers to increase optical energy absorption band,[53] nanosilver containing electrodes to improve aging stability in solar cells,[54] nano chalcopyritic powders using solvothermal synthesis modified by use of microwave heating for use in polymeric thin film solar cells, [55] and incorporation of carbon nanotube to improve cell efficiency.[56]

There are also several published articles on the use of nanotechnology in solar cells. Polyaniline film with nanoislands have been coated electrochemically for use as anode buffer in organic solar cells which led to improvement in performance (Furui et al., 2011). Three-dimensional nano-networked growth of poly-3-methyl-thiophene was obtained by electrochemical technique which led to improved performance when used as donor in an organic solar cell (Gao, 2011). Anode with patterned dots of 50 or 200 nm depth has been prepared by nano-imprinting technique for organic solar cells (Wang et al., 2010b). Nanosilver inserted multilayer $ZnSnO_3$ electrode has been developed as a low cost indium-free option for inverted organic solar cells (Choi, 2011b).

In the case of dye sensitized solar cells, there are many published reports on use of nanomaterials. TiO_2 nanoparticles on TiO_2 nanotubes grown on Ti substrate led to improved performance (Yun et al., 2011). Rutile with nano-branched morphology has been prepared using wet chemical method (Wang et al., 2011a). Vacuum cold spraying using strengthened nano TiO_2

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[51] Kumar MS, DV Vishnu, HS Mujavar, and OS Balkrishna, "High efficient dye-sensitized solar cells using Tio2- multiwalled carbon nano tube (MWCNT) nanocomposite", European Patent Application No. WO2010IN00023201 00112.

[52] Zook David J, Marcus Matthew S, Liu Yue, 2010, "Nano-structured solar cell" European Patent EP2264780 (A2).

[53] Oku Takeo, Kikuchi Kenji, Suzuki Atsushi, Nagata Akihiko, Osawa Eiji, and Yamazaki Yasuhiro, 2011. "Organic nano carbon compound system thin film solar cell", Japanese Patent No. JP2011054631 (A).

[54] Yoshiaki T, Y Kazuhiko, and H Toshiharu, "Composition for forming electrode for solar cell, method of forming electrode, and solar cell using electrode obtained by method", Patent Application No. JP20090040645 20090224.

[55] Huang Y, BJ Hwang, HF Wang, CC Wu, and SH Chang, 2009. "Fabrication methods for nano-scale chalcopyritic powders and polymeric thin-film solar cells", US Patent Application No. 20090317939.

[56] Flood DJ, 2011. "Nanostructured solar cells", US Patent Publication No. US 7999176 B2.

powder has been used to obtain nanoporous TiO_2 film (Yang et al., 2011). Nano TiO_2 has been coated on ZnO nanorods (Chao et al., 2010). Graphene coated with MWCNT has been synthesized as a counter electrode (Choi et al., 2011c). Amorphous carbon made with spray coating of a solution containing nanocarbon dispersed in ethanol has also been used as a counter electrode (Veerappan et al., 2012).

Nanorods have been deposited on zinc-coated indium tin oxide glass by electrochemical method. Cu_2O film was then coated electrochemically on the nanorods. This led to better efficiency of the ZnO/Cu_2O heterojunction cell (Chen et al., 2011a). Nano patterns on Si using lithography led to improvement in performance by reducing reflection and increasing optical absorbance (Liu et al., 2011). Nanotexturing of silicon surface using wet chemical etching using silver catalyst and hydrofluoric acid and hydrogen peroxide led to reduction in reflectivity (Srivastava et al., 2012). Wet nanotexturing has been done on mono-crystalline Si solar cells to reduce reflectance (Chang and Jung, 2011). Nano imprint lithography has been used for reducing reflectance in GaAs tandem solar cells (Han, 2011). Development of a nano Pt-MWCNT counter electrode has also been reported (Huang et al., 2012).

3.2.3 Hydrogen storage

Hydrogen is an environment friendly fuel and its storage is a key requirement, especially for mobile applications. Many nanomaterials have been developed for hydrogen storage and some of them have been reported by companies. Nanoporous hydrogen storage polymers have been prepared by electro-spinning or electro-spraying in which chemical hydrides are trapped.[57] A technology for preparing nanostructured cast magnesium alloy for hydrogen storage as metal hydride has been reported.[58] Laser hydrides with nanostructures which release hydrogen upon exposure to laser light have been developed.[59]

Several patents have been filed on hydrogen storage materials. Nano foils of platinum prepared by magnetron sputtering has been reported for

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[57] Cella Energy Limited, http://www.cellaenergy.com/index.php?page=technology, (last accessed: March 2012).

[58] Hydrexia Pty Ltd, http://www.hydrexia.com/technology.htm, (last accessed: March 2012).

[59] http://www.careh2energy.com/CH2ELaserHydrides.html, (last accessed: September 2013).

hydrogen storage.[60] Development of an advanced method for preparing organic-transition metal hydride has been reported which has the advantages of fewer by-products and moderate reaction conditions.[61] Storage of hydrogen using nanostructured mats made of nanowires or nanosprings of glass, ceramics or ceramic oxides deposited on a substrate has been patented.[62] To improve the storage capacity, oxidation of a microporous activated carbon to develop mesoporous and nanoporous channels, and nanopores followed by impregnation of platinum has been reported.[63] To avoid the disadvantages of particle compaction and settling of particle bed while using powder hydrogen storage materials, composites formed by addition of binder and other compounds for improving properties followed by moulding to the required shape has also been reported.[64]

There are several research publications involving use of nanomaterials in hydrogen storage. The addition of nanocatalysts to improve the adsorption capacities as well as the adsorption desorption rates of simple metal and complex metal hydrides has been reviewed recently (Varin et al., 2011). Addition of nanometals such as Ni, Co, Fe, Cu, Mn to borohydrides, metal hydrides, and amides has led to reduction in hydrogen release temperature and increase in rate of release (Srinivasan et al., 2010).

3.2.4 Lithium ion batteries

Lithium ion batteries are rechargeable batteries with high energy density and low loss of charge when not in use. They are commonly used in consumer electronic items. Nanotechnology has been used for improving the

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60 Onishi S and M Calves, 2011. "Hydrogen storage nano-foil and method of manufacture", US Patent No. 8,083,907.

61 Kim JS, DO Kim, HB Yoon, J Park, HJ Jeon, GR Ahn, DW Kim, J Ihm, and MH Cha. "More advanced preparation method of organic-transition metal hydride complexes containing aryl group or alkyl group as hydrogen storage materials", Patent Application No. EP20090010344 20090811.

62 Norton G and D McIlRoy, 2010. "Apparatus with high surface area nanostructures for hydrogen storage, and methods of storing hydrogen", US Patent No. 7771512.

63 Tsao CS, MS Yu, YR Tzeng, CY Wang, HC Wu, TY Chung, CC Chien, and LF Lin, 2011. "High capacity hydrogen storage material and method of making the same", US Patent No. 7927693.

64 Zimmermann J, 2010. "Composite hydrogen storage material and methods related thereto", US Patent No. 7708815.

performance of lithium ion batteries and nanomaterials are being developed by different companies. Nano film anodes and nanostructured lithium manganate cathode have been prepared. These gave rise to faster charge/discharge, high energy density, and high specific capacity which does not drop with cycling.[65] Nanomaterials such as lithium titanate, lithium cobalt oxide, and thin film SnOx solid composite electrolyte are being developed by a company for improving performance of lithium ion battery.[66] To improve safety, the reactive graphite in lithium ion battery has been replaced with nano titanate, suitable for a wide range of temperature and with life long.[67] Nano silicon composite additive has been developed for lithium ion battery anode which increases capacity without compromising on cycle life.[68] Other materials developed for anode include carbon nanofibre paper coated with silicon[69] and a high capacity anode based on nano silicon.[70]

There are several patents covering the use of nanomaterials in lithium ion batteries. A recent report has analysed the patents on this topic and has found that the maximum number of patents focus on nanomaterials for anode.[71] An anode made of superconducting nanocarbon coated with materials such as Sn, Si, Ni, and Al has been patented.[72] There is also a patent on Si nanowires with metal nanoclusters (Ag, Au, Ni, Cu) for use in lithium batteries as well as other applications.[73] An anode comprising

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65 MetaMateria Technologies, http://www.metamateria.com/BatterySummary82010.pdf, (last accessed: March 2012).

66 nGimat Co., http://www.ngimat.com/pdfs/Nanomaterials_Lithium_Ion_Batteries.pdf, (last accessed: March 2012).

67 Ecoworld, http://www.ecoworld.com/energy-fuels/nano-titanate-car-batteries.html, (last accessed: May 2013).

68 Nanosys, Inc., http://www.nanosysinc.com/what_we_do/energy_storage/, (last accessed: March 2012).

69 Firsich WD, 2010, Silicon modified nanofiber paper as an anode material for a lithium secondary battery, US Patent Application 20090068553.

70 Amiruddin S and B Li, 2013. "High capacity lithium ion battery formation protocol and corresponding batteries", US Patent 20130043843 A1.

71 NanoWerk, 2011. "Patent analysis and product survey on use of nanomaterials in lithium-ion batteries" http://www.nanowerk.com/spotlight/spotid=21950.php (last accessed: March 2012).

72 Lee SR, JM Kim, KN Joo, JH Lee, TS Kim, S Do, YS Kim, DH Kim, GH Chung, BK Kim, YM Yu, and CS Shin, "Negative active material and lithium battery", Patent Application No. EP20110164156 20110428.

73 Samsung Electronics Co Ltd; 2011, "Silicon Nanowire Comprising Metal Nanoclusters and Method of Preparing the Same", Japanese Patent JP2011219355 (A).

metal-coated fullerene deposited on a conducting layer to form a high surface area anode has been reported.[74] Carbon nanofibre containing metal oxide or intermetallic prepared by electrospinning has been patented.[75] A cathode material containing carbon nanotube with an outer layer of silicon, antimony or germanium and an outer layer of amorphous carbon has been patented.[76] A composite core shell cathode comprising lithium iron phosphate or a lithium manganate core and lithium iron phosphate with carbon nanotube shell has been prepared.[77]

There are also several research publications on the use of nanomaterials in lithium ion batteries. Coating of nano lithium phosphate on lithium manganese oxide has shown to reduce charge transfer resistance and improve performance (Li et al., 2012a). A lithium ion cell with nano-sized TiO_2-based anode and ZnO-coated lithium nickel manganese spinel was tested to circumvent the problem of losses during cycling (Brutti et al., 2011). Silicon due to its high energy density is a good additive for the anode but it has the problem of large volume changes during the charging and discharging cycles. The potential of preventing this volume change by encapsulating silicon nanowires with carbon nanotubes has been examined by computational modelling (Zang and Zhao, 2012). Several nanomaterials have been studied for anode such as $Li_4Ti_5O_{12}$/Sn nanocomposites (Sivashanmugam et al., 2011), activated carbon containing graphene, nano graphite and nanoparticles of tin oxide (Li et al., 2012b), porous Co_3O_4 nanoneedles on copper foils (Xue et al., 2011), anatase nanotubes with uniform wall thickness (Panda et al., 2012), SiO_x/C nanocomposite (Wang et al., 2011b), Fe_3O_4/carbon nanocomposite (Jin et al., 2011), spinel $Li_4Ti_5O_{12}$ (Wu et al., 2012b), $Li_4Ti_5O_{12}$/Ag nanocomposite (Liu et al., 2012), gold-coated

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[74] Sergey DL, L Christopher, and ZB Robert, "Three-dimensional battery with hybrid nano-carbon layer", US Patent No. 2010/0151318.

[75] Lee WJ and HR Jung, "Carbon nanofiber containing metal oxide or intermetallic compound, preparation method thereof, and lithium secondary battery using same", Patent Application No. WO2011KR05041 20110708.

[76] Kim KT, SH Ahn, JY Kim, J Cho, and MH Park, "Cathode active material for a lithium rechargeable battery and a production method therefore", Patent Application No. WO2010KR03910 20100617.

[77] Kong L, X Ji, and Y Wang, "Composite positive electrode material with core-shell structure for lithium ion battery and preparing method therefore", Patent Application No. WO2010CN77446 20100929.

porous silicon films (Thakur et al., 2012), and NiO graphene (Mai et al., 2012). A new concept for eliminating Li metal using silicon carbon nanocomposite anode, sulphur carbon composite anode and glycol based electrolyte has been published (Hassoun et al., 2012).

3.2.5 Capacitors

Electric double-layer capacitors — also referred to as super-capacitors/ultra-capacitors/electrochemical double layer capacitors — have a much higher energy density than conventional capacitors. They have the advantages of fast charging and ability to release energy over a small duration such as required in vehicular applications. They use nanoporous materials, particularly carbon, as electrodes.

There are several recent patents dealing with nanotechnology in capacitors. One patent describes the growth of carbon nanotubes to get vertically aligned tubes using graphene as a mask which was done to improve the capacitance.[78] Another describes a modification of the halogenation of metal carbides to obtain nanoporous carbons by performing in-situ oxidation to broaden the surface pores to improve access which leads to increased energy density for super-capacitor applications.[79] Electrodes for ultra-capacitors made of halloysite clay microtubules have been described in a patent to improve the charge storage potential.[80] Polymer containing nanodomains with ionic conductivity has been developed and applied for ultra-capacitors.[81] Nano graphene platelets have been developed and one of their applications is in super-capacitors. A spinoff company has been created to make nano graphene platelets for super-capacitor electrodes which have better performance compared to using other nanocarbon forms such as tubes or fibres.[82] A patent application has been filed for super-capacitor

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78 Jang CH, 2011. "Manufacturing method of capacitor in semiconductor", US Patent 7939404.

79 Leis J, M Arulepp, M Latt, H Kuura, 2010. "Method of making the porous carbon material of different pore sizes and porous carbon materials produced by the method", US Patent 7,803,345.

80 Gunderman DR and MJ Hammond, 2010. "Ultracapacitors comprised of mineral microtubules", US patent US 7679883 B2.

81 Cao L and SG Ehrenberg, 2011. "Nanoparticle ultracapacitor", US Patent 7,990,679.

82 Angstron Materials Inc., http://www.angstronmaterials.com/, (last accessed: March 2012).

with nano graphene platelet based electrode.[83] A patent describes the use of conductive nanowire electrode to obtain miniaturized capacitor without compromising the performance.[84] Insulating nanoporous oxides have been used as part of a composite electrode for ultra-capacitors with improved energy storage.[85]

Nano barium titanate has been prepared for ceramic polymer composite capacitor (Lee et al., 2010). A nanocomposite comprising mesoporous carbon coated with a nanolayer of polypyrrole has been prepared for electrochemical capacitor (Zhang et al., 2010). Nano zirconia carbon black composites have been studied as electrochemical double layer capacitor electrode (Nasibi et al., 2012). Nano bernissite Na_yMnO_2 nH_2O has been prepared and used as positive electrode in an electrochemical capacitor (Komaba et al., 2012). Nano manganese oxide has been tested as electrode material for hybrid super-capacitor (Yuan et al., 2010). Nanoparticles of TiP_2O_7 have been prepared by combustion synthesis method and used in hybrid super-capacitor (Aravindan et al., 2011). Lithium titanate impregnated on carbon nanofibre has also been used as electrode for hybrid capacitor (Naoi et al., 2010). Given the increasing use of carbon nanotubes instead of activated carbon in super-capacitors, a recent study has compared solution electrode fabrication methods and has determined that the key factors influencing performance are related to material loss and contamination (Ervin et al., 2012). Nano spheres of Mn_3O_4 were prepared by electro-deposition and showed high electrochemical properties (Yousefi et al., 2012). In an attempt to maximize electrochemical performance, metallic and semiconducting single-walled carbon nanotubes (SWCNT) were separated by gel chromatography and characterized and the semi conducting SWCNT had more capacitance (Yamada et al., 2012). MWCNT electrodes have been used along with a Li_2S-P_2S_5 glass ceramic electrolyte and were found to develop reversible double-layer capacitance.

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83 Yu Z, D Neff, C Liu , B Z Jang, A Zhamu, 2012. "Supercapacitor with a meso-porous nano graphene electrode", US patent application 20120026643.

84 Shioya S and S Ikeda, 2011. "Nano-wire capacitor and circuit device therewith", US Patent 7906803.

85 Anderson MA and KC Leonard, 2009. "Nanoporous insulating oxide electrolyte membrane ultracapacitor, button cell, stacked cell and coiled cell and methods of manufacture and use thereof", US patent 20090154060.

3.3 Nanomaterials in Environmental Applications

3.3.1 Water and wastewater treatment

Membrane filtration — covering processes such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) — is a well-established technology in water treatment for selective permeation of the desired components. The applications cover removal of a variety of components such as particulate matter, colloids, macromolecules, salts, etc., from the feed water. The membrane properties determine the separation characteristics and thus one key aspect of membrane research targets development of improved membranes for various applications.

Modifications in membrane materials using nanotechnology have been made such as nanocomposite hybrid membranes for high selectivity, incorporating nanoparticles for fouling prevention (OECD, 2011). NF membranes have been tested for removal of various contaminants such as organic pollutants, cations, biological contaminants, etc. (Savage and Diallo, 2005). NF membranes have also been used for desalination. It has been reported that its use as a pre-treatment for RO or multistage flash evaporator led to 60 per cent increase in production and 30 per cent reduction in cost (Abdul-Kareem, 2001). There are many companies manufacturing these membranes[86] and the applications have been discussed in a comprehensive review (Hilal et al., 2004). RO membranes have been used extensively for drinking water treatment, sea water desalination, and in the final stages of wastewater treatment for reuse. New thin film nanocomposite RO membranes with high permeability and salt rejection have also been developed (Lind et al., 2010) and are now commercially available.[87] Development of ceramic membranes in the ultrafiltration (UF) range with nano ferroxane has been reported (Cortalezzi et al., 2003). Other nanoparticles such as silver, silica, titiania have been incorporated for specific functionalities (Zhang et al., 2012).

Nano Zerovalent Iron (ZVI) has attracted a lot of attention for in-situ groundwater remediation. This is motivated by a well-established science in using non-nano ZVI combined with improved remediation and deployment

[86] http://www.thomasnet.com/products/nanofiltration-membranes- 50491968-1.html, (last accessed: May 2013).

[87] NanoH_2O, Inc. http://www.nanoh2o.com/, (last accessed: November 2012).

capability. However, the ecological and human health risks of nano ZVI are not yet fully understood (Tratenyek and Johnson, 2006). There are many research activities in this area covering different preparation methods and contaminants (Yaacob et al., 2012; *ObservatoryNANO focus report*, 2010). There are also companies manufacturing this material.[88] Field trials have also taken place for removal of contaminants such as polychlorinated biphenyl, trichloroethylene, dichloroethylene, etc. (Gavaskar et al., 2005; Woodrow Wilson International Centre for Scholars 2013). The use of nano ZVI in distillery wastewater treatment has been investigated in laboratory scale and showed removal of colour as well as chemical oxygen demand (COD) and biochemical oxygen demand (BOD) (Homhoul et al., 2011).

Carbon nanomaterials have been studied for water/wastewater treatment. They have the advantages of high surface area to volume ratio, controlled pore size distribution, and tunable surface chemistry. There are various reviews covering their applications as sorbents, aligned carbon nanotubes as high flux membranes, coating on ceramic membranes, environmental sensors (Mauter and Elimelech, 2008; Upadhyayula et al., 2009). Carbon nanotubes have been incorporated in polymer matrix for obtaining composite membranes with fouling control (Celik et al., 2011; Ajmani et al., 2012). Carbon nanotubes has been grown in sponge form for oil removal and nanoparticle removal (Gui et al., 2010). However, issues of cost, product quality fluxes, transport, and toxicity remain.

Materials such as nanometals and metal oxides have been used as biocides and dendrimers that can bind specific components. Nanosilver has been used in some commercial water treatment products.[89] Dendrimers have also been used to bind bactericide and when the material is in contact with water, bacteria is killed (Tansel, 2008). Catalysts in the nanoform have been investigated for removal of contaminants, such as chlorohydrocarbons. For instance, Pd on nano gold showed very high activity, almost 100 times to that of Pd alone (Wong, 2010). Other nanocatalysts such as Pd-Fe_3O_4 (Hildebrand et al., 2009), iron oxide (Zhong et al., 2006), chitosan-nano CdS (Zhu et al., 2009), and nanosilver carbon on alumina (Shashikala et al., 2007) have also

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[88] Nano Iron, S.R.O,.http://www.nanoiron.cz/ ; (last accessed: November 2012).

[89] Aqua-Win Water Corporation, Available athttp://www.aquawin.com.tw/category/nano-silver-activated-carbon-filter.htm, (last accessed: November 2012).

been studied. Nanophotocatalysts such as TiO_2 have been used for both organic and inorganic contaminants (Chen et al., 2003; Yang et al., 2012).

3.3.2 Air pollution control

Catalytic breakdown of pollutants is a commonly used approach in air pollution control and different nanocatalysts have been developed for this application. This includes nanoforms of gold, cobalt, platinum, etc. There are also companies manufacturing nanocatalysts such as Nanostellar Inc. and Poriferia.[90] Air filters with nanophotocatalysts are being offered by some companies.[91] Nano gold supported on mesoporous MnO_2 has shown good activity for volatile organic compounds (VOC) removal at room temperature (Sinha et al., 2007). Silica-titania nanocomposite has been tested for photocatalytic removal of mercury from coal combustion flue gas (Ying et al., 2008). Deposition of MWCNT on glass fibre air filter was found to increase efficiency for aerosol and bacteria removal (Park et al., 2011). NOx reduction has been studied using nanocatalysts such as gold on ceria and ceria-alumina (Ilieva-Gencheva, 2008), and vanadium pentoxide on titania (Chen et al., 2011b). Nano copper based catalysts have been examined for VOC oxidation (Kim and Moon, 2011). Nano platinum on ceria was found to be highly efficient for the oxidation of carbon monoxide and acetaldehyde (Fuku et al., 2013). Nano platinum on alumina-ceria support has shown high activity for oxidation of toluene and xylene (Abbasi et al., 2011). Composite nanowires of zinc oxide or titania and perovskite have been developed for emissions control for automobile and industrial applications (Gao, 2011).

Nanomaterials have been used for CO_2 removal or separation and the use of nanoporous materials for this application has been recently reviewed (D'Alessandro and McDonald, 2011). Nanoporous clays with amine modification have shown high adsorption capacities (Pinto et al., 2011). Nano CaO coated with $CaTiO_3$ has been prepared with better sorption capacity and durability (Wu and Zhu, 2010). Nano CaO alumina sorbent has been reported for high temperature CO_2 adsorption (Wu et al., 2008). Nano molecular sieves

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[90] Earl Boysen. Available at http://www.understandingnano.com/air.html. (last accessed: March 2012).

[91] Green Earth Nano Science, Inc. Available at http://www.greenearthnanoscience.com/air-purification.php. (last accessed: March 2012).

[92] Liu C and ST Wilson, "Nano-Molecular Sieve-Polymer Mixed Matrix Membranes with Significantly improved gas separation performance", US patent 20070209514.

have been added to polymer matrix to obtain membranes suitable for CO_2 separation from methane.[92] Addition of carbon nanotube to polymeric membrane for biogas purification led to improved permeability and strength (Kusworo et al., 2010). A nanostructured plastic membrane for CO_2 capture has been developed which converts CO_2 to bicarbonate with a fixing agent that then passes through the membrane.[93]

3.3.3 Sensors

Nanomaterials in sensors offer advantages in terms of low power required, greater sensitivity, and response time (Harnett, 2010). There is also potential for detection with a smaller sample size,[94] higher selectivity, and capability for detecting multiple components.[95] For different applications, nanoforms such as particles, rods, wires, porous materials have been used (Riu et al., 2006).

Carbon nanotubes have been studied with other materials for different sensing applications (Kauffman and Star, 2008). Carbon nanotube with palladium has been used for hydrogen sensors with a detection limit of 100 ppm (Syed et al., 2007). Carbon nanotube has been used for organic vapour and other gas detection and detection limits of 44 ppb for NO_2 and 262 ppb for nitrotoluene have been reported (Jing et al., 2003). Gold has been deposited on carbon nanotubes electrochemically for use as pesticide sensors (Zhang et al., 2009).

The applications of metal oxides in the nanoform for sensing have been reviewed. Examples include humidity measurement with nanoporous alumina and hydrogen detection with titania nanotubes (Varghese and Grimes, 2003). Single crystal lead zirconate titanate nanowires were used in a nanogenerator for detecting UV irradiance (Bai et al., 2012). Nanoporous Ta_2O_5 membranes have been used for sensing of gases such as NH_3, CO, H_2, NO_2, and it was observed that the performance was good at high temperatures (Imbault et al., 2012). Cobalt-doped antimony oxide nanoparticles showed high sensitivity and fast response time for detection of dichloromethane (Jamal et al., 2012). Porous V_2O_5

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93 Oksholen T, 2008. "New membrane catches CO_2". Available athttp://www.ntnu.no/gemini/2008-english/6.htm.(last accessed: November 2012).

94 NJ Tao, 2004. "Nanotechnology Applications for Environmental Sensors:Integrated Devices for Real-Time Analyses". Available at http://epa.gov/ncer/publications/workshop/8-18-04/pdf/tao_EPA04a.pdf. (last accessed: November 2012).

95 Filipponi L and D Sutherland, 2007. "Applications of Nanotechnology: Environment". Available at http://www.nanocap.eu/Flex/Site/Download2e90.pdf.

nanotubes have been used in a humidity sensor which had quick response time and recovery (Yin et al., 2012).

3.4 Summary

In the energy applications discussed in this chapter, it is seen that a variety of nanomaterials are being explored to move towards the required performance, cost, and commercialization targets. In fuel cells, the focus has been on catalysts and electrolyte for improved performance. Other issues such as humidity management in PEMFCs and low temperature operation in SOFCs have also benefitted from the use of nanomaterials. In case of solar cells, nanomaterials have contributed to greater efficiency, ease of manufacture, and lower cost. Use of nanomaterials in lithium ion battery electrodes and electrolytes have been examined with a view to improving energy density, achieving faster charge/discharge, reducing losses during cycling. Similarly, in capacitors, nanomaterials for improved performance and energy density have been studied. In environmental applications, there are some commercial products with nanomaterials in case of water filters and air filters. In most other areas, the development is at a research or prototype stage. In spite of the advantages offered, the concerns are more due to possible transport and toxicity of the nanomaterials at the stage of product use (e.g., nano ZVI for groundwater remediation, nanosilver in water filters). Thus, irrespective of the applications, the issues of safety and risk, product recycling at end of life of the product, and net lifecycle advantages should not be ignored. These aspects need to be explored further.

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CHAPTER 4

Environment, Health, and Safety Implications of Nanotechnology: Concerns for India

Shilpanjali Deshpande Sarma

4.1 Introduction

The development and application of technologies including emerging technologies such as information technology and biotechnology has propelled socio-economic and industrial progress in developed and developing nations. Nevertheless, technology-based applications whilst providing innumerable societal benefits have also resulted in environment and health concerns. Risk is defined as 'the potential for the realisation of unwanted or adverse consequences to human life, health, property or the environment' (Renn, 2005). Health problems and environmental degradation resulting from pesticides, asbestos, chloro-fluorocarbons, e-waste, and industrial pollution are a manifestation of risks that can emerge from ill-informed and ill-equipped systems for management of potential hazards. Undoubtedly, technology development, especially in the nanotechnology domain, can provide developing countries such as India immense opportunities and benefits. However, sustainable development of nanotechnologies can only emerge if simultaneous attention is paid to addressing potential safety concerns. Therefore, in order to develop adequate frameworks to ensure environment, health and safety, it is imperative to understand and anticipate potential environment and health issues surrounding the development of nanotechnologies.

Nanotechnology, that spans numerous and disparate technologies, is based on the manipulation and application of diverse nanomaterials that are in the nanometer range. Nanotechnology has been the focus of S&T policies of numerous countries for its ability to enable significantly enhanced or novel products and processes which can contribute immensely to diverse sectors of economic and social interest. However, despite these potential benefits, the inherently complex and transformative nature of nanotechnologies raises significant questions and concerns with regards to the risks they might pose to society. Humans and ecosystems have for centuries been exposed to certain kinds of nanomaterials that either materialize naturally in environments or which can be formed as a by-product of human activities. However, the recent ability to synthesize, manoeuvre, and assemble nanoparticles has opened up opportunities to produce novel nanomaterials with unique and unusual properties in previously unanticipated volumes. Since nanomaterials can be utilized in various applications benefiting several sectors, there now exist greater opportunities for human and environmental exposures to these materials. This raises several questions with regards to their potential impact and safety. What is the nature and extent of the concerns from nanotechnologies? What determines the environment and health effects? It is essential that developing countries such as India that are experiencing nanoproduct commercialization have a clear understanding of these issues and also examine safety implications of specific products in order to effectively manage the risks and regulate impacts.

4.2 Factors Prompting Safety Concerns from Nanotechnologies: Issues and Challenges for Governing Risks

What makes nanomaterials unique is the fact that at a scale of 1–100 nanometers materials are of minute size and possess physio-chemical properties different from conventional chemicals that are larger in size. Besides the fact that nanotechnology comprises nano-scale versions of numerous existing elements and compounds, it also enables the development of altogether new kinds of materials such as carbon nanotubes and fullerenes. Nanomaterials lie in between atomic/molecular scales and bulk-sized chemicals and display unusual qualities. The small size of these nanomaterials endows them with large surface areas which can make them more reactive than their larger analogues. It also prompts changes in characteristics such as binding and absorption, strength, conductivity as well as electronic, optical, and magnetic properties. Overall, these properties are influenced by the size, shape, chemical composition, surface structure, etc., of the nanomaterial (Nel et al., 2006; Krug et al., 2008a). Given that nanomaterials possess these unique properties, they can also have environment and health impacts different from those observed from conventional chemicals. While this does not automatically imply that all nanomaterials could be potentially hazardous, it certainly indicates that the safety of nanomaterials cannot automatically be inferred on the basis of that of their comparable conventional or larger counterparts.

Physicochemical properties such as particle size and size distribution, agglomeration state, shape, crystal structure, chemical composition, surface area, surface chemistry, surface charge, solubility, and porosity are important in understanding the toxic effects of test materials (The Royal Society and the Royal Academy of Engineering, 2004; Oberdörster et al., 2005; Saliner et al., 2009). By virtue of their size, nanomaterials might be able to enter the human body and those of other species imperceptibly through various routes, penetrate organs, and pass through cell membranes to reside in cells. The surface characteristics of the nanoparticle largely determine its distribution in the body and its accumulation in organs and cells while its reactivity influences its ability to take part in reactions that might release free radicals causing oxidative stress (The Royal Society and the Royal Academy of Engineering, 2004). However, other factors too influence hazard potential. For instance, in the case of some nanoparticles such as quantum dots, environmental conditions (Derfus, 2004) and their stability (photolytic, oxidative, and mechanical stability) appear to play a role in determining toxicity (Hardman et al., 2006). Under oxidative and photolytic conditions, shell coatings on the quantum dots can become labile, facilitating more than one avenue for manifestation of potential toxicity — from exposure to toxic capping material, intact core metalloid complexes or the core metal components after the dissolution of the metalloid complex. In other cases as with carbon nanotubes, it has been suggested that ecotoxicity might be determined not just by the nanomaterial but also by the metal and amorphous impurities that are generated during carbon nanotube manufacture and which coexist with the carbon nanotubes (Berger, 2008).

Overall, nanomaterials comprise a diverse group of materials from metals and metal oxide nanoparticles (e.g., silver and gold nanoparticles as well as zinc oxide and titanium oxide) and nanowires (e.g., silicon, gallium nitride) to carbonaceous materials (e.g., carbon nanotubes, fullerenes and grapheme), quantum dots (e.g., lead and cadmium sulphide) as well as nanocomposites, etc. Therefore, the human and environmental effects of individual nanomaterials might vary. As stated by Hoet et al. (2004), in their study, 'there is no universal "nanoparticle" to fit all cases, each nanomaterial must be treated individually when health risks are expected'. Yang et al. (2009) identified four types of nanomaterials and explored the interrelationship between particle size, shape, chemical composition, and toxicological effects. In this case, it was observed that metal nanoparticles were more cytotoxic (inducing cell death) than non-metallic nanoparticles whereas carbon nanotubes though less cytotoxic appeared to cause more DNA damage than the former. Therefore, in this case, chemical composition influenced cell death or cytotoxicity while genotoxicity was determined by particle shape. Besides the nanomaterials themselves, coatings applied to nanomaterials to alter or improve functionality add to the diversity of nanomaterials. While coatings can be utilized to mitigate the toxic potential of specific nanomaterials, they might also otherwise be hazardous in their own capacity.

Risk is influenced by both the magnitude of the hazard as well as the likelihood of exposure to the hazard. Therefore, besides hazard potential which is indicated by toxicity, the likelihood of exposure to nanomaterials also influences the manifestation of risks from nanotechnologies. Hence, the magnitude and frequency of the exposure to the nanomaterial as well as the route of exposure are important in determining the potential impacts from nanomaterials. Nanomaterials have already been incorporated in a variety of products ranging from cosmetics and personal care products, textiles and sports goods, pharmaceutical and electronic products, paints and other coatings, catalysts and in some case even in home care and food products. Utilization of nanomaterials to develop applications in the areas of water, energy, and environment is underway. With over 1,000 products in the market[1] and given the large investments in applied research, it is

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[1] The Project 'Emerging Nanotechnologies, 2013. Consumer Products Inventory. Available at http://www.nanotechproject.org/cpi/about/analysis/ (last accessed: December 2013)

not unreasonable to anticipate that several new nanoproducts will be commercialized in the future as more research bears fruit and drives companies towards commercialization. Given this scenario, several routes of exposure might exist along the life cycle — manufacture, consumer usage, and disposal — of nanoproducts which can lead to the exposure of humans and other species to nanomaterials. Already in research institutes and production facilities, nanomaterial synthesis is being undertaken that brings workers and researchers in contact with nanomaterials making occupational safety a serious concern.

Besides these issues, there are other challenges that emerge from the pace of nanotechnology developments in society. The intense focus on technology development has ensured that R&D advancements and commercialization is evolving rapidly whereas understanding on potential environmental and health impacts has not kept pace with these developments. Under-emphasis of research and management of the potential risks has led to knowledge gaps on the safety implications of existing nanomaterials and nanoapplications. Furthermore, given its transformational nature and ability to converge with other technologies, there is unpredictability about the ways in which sophisticated and advanced nanotechnologies could impact society.

At the global level, vital knowledge gaps prevail in the context of toxicity and exposure scenarios for nanomaterials and nanoproducts. In terms of building comprehensive information on risk potential, there exists a lacunae in the breadth of studies being undertaken for risk assessments. While the domain of nanotoxicology is expanding, there is relatively less information on environmental fate and behaviour of nanomaterials in air, water, and soil. Knowledge on kinetics of nanomaterials in the human body and effect of chronic exposures is also rudimentary. Furthermore, although nanomaterial production and use of nanoproducts present opportunities for exposures, appropriate tools for detecting and measuring nanomaterials in various environments are still largely in development, are expensive or inaccessible, especially in developing nations.

Challenges also exist in developing nomenclature and definitions, dosage metrics and standards for nanotechnologies, and also for arriving at standardized methodologies for risk evaluations. For instance, due to the inherent differences in the properties that nanomaterials display vis-à-vis their bulk analogues, their toxicology cannot be directly inferred from that of the larger analogues. In effect, this implies that in order to understand environment and health impacts of these materials, various nanomaterials would most likely need to be subjected to individual risk assessments which places a significant burden on regulatory authorities. Additionally, the fact that different parameters could significantly influence the toxic potential of nanomaterials, has posed a unique problem for developing dose-response metrics which are needed to derive conclusions on toxicity. With regard to bulk materials, dose metrics which are based on the concentration or mass of the substance in the surrounding medium or environment has been found to deliver a good correlation with the toxicity potential of such substances. Yet, in the case of nanomaterials, the metric — mass, surface area, particle number, etc. — that could provide the best correlation with toxicity remains elusive as it might vary for specific nanomaterials. This is adding to the delay in the formulation of regulatory thresholds for exposure.

Knowledge gaps, such as those described here, hamper adequate risk regulation and governance at national and international levels raising concerns for the safe development of nanotechnology. As R&D investments and initiatives for nanotechnologies move from developed country confinements to developing country shores creating resource destinations and markets with trans-national dimensions, the ramifications from the development and use of nanotechnologies could be felt not only in local contexts but also more broadly at regional and global levels. Currently, efforts to remedy these deficits are underway in developed nations. However risk governance for nanotechnologies remains under-developed in developing nations such as India and this is problematic, especially since the expansion of nanotechnology R&D is taking place in the absence of adequate efforts for understanding and managing risks.

4.3 Examining Evidence for Exposure and Hazards from Nanomaterials

4.3.1 Pathways for human exposure

Studies on mammalian systems have identified that the major routes for human exposure to nanoparticles are through inhalation, dermal contact, and ingestion.

4.3.1.1 Inhalation

The small size of nanoparticles makes them very amenable to entry into lungs and into the alveoli via inhalation. This is the most likely route for exposure in occupational set-ups and in the general environment, if nanoparticles are present in the surrounding atmosphere. Although particles might be cleared from the lungs as long as the clearance mechanisms are not affected, nanoparticles are very likely to hamper these processes, resulting in increased deposition of such particles amplifying any chronic effects. Nanomaterials that are shaped like fibres, especially nanofibres, are most prone to accumulation in the lungs, their length determining the possibility for clearance. Studies in rodents suggest that significant amounts of carbon particles travel from the nose via the olfactory nerve to the central nervous system (Oberdörster et al., 2004). Rapid translocation of nanoparticles through the blood stream to other vital organs is also possible after inhalation (Nemmar et al., 2001; Simkó et al., 2010; Geiser and Kreyling, 2010). Recent publications on the pulmonary effects of carbon nanotubes indicate that nano-sized fibre can induce a general pulmonary fibrotic response (Mercer et al., 2011).

4.3.1.2 Dermal contact

Several products such as textiles, cosmetics, sunscreens, and other personal care products that contain nanoparticles of different kinds now exist in the market. Titanium di-oxide nanoparticles are favoured in sunscreens over the use of conventional-sized particles as they improve the transparency of the cream; silver nanoparticles have been incorporated as antibacterial agents in bandages and gels for medical uses. Silver nanoparticles have also been integrated into fabrics that are used as shirts, socks, etc. The use of these products provides a route for dermal contact to nanoparticles present in these products.

The external layer of the human skin, the stratum corneum, provides an effective barrier that protects the internal systems in the human body from the external environment. It is in fact a mechanically strong and resilient structure that can withstand physical strain and stress. Yet, nanoparticles being extremely tiny in size can pass through the pores of the skin which provides an entry point for their interaction with the internal systems. Recent studies have shown that quantum dots are capable of penetrating through the dermis of the skin samples (Rayman-Rasmussen, 2006; Mortensen et al., 2008; Zhang and Monteiro-Riviere, 2008). In other research using in-vitro testing, dermal exposure to multi-walled carbon nanotubes (MWCNT) was examined. In this study on MWCNT exposure, the human epidermal kerationocytes showed cytokine-mediated inflammatory response (Monteiro-Riviere et al., 2005). A more recent study that tested inflammatory responses in human N-hTERT telomerase-immortalized keratinocytes revealed that the inflammatory pattern of MWCNTs in N-hTERT cells, included various other cytokines. They however concluded that the cornified layer provides an efficient barrier against MWCNTs (Vankoningsloo, 2012).

4.3.1.3 Ingestion and other routes

Ingestion as a route of exposure to nanoparticles would be possible in case of consumption of food or beverage products or drugs that contain nanoparticles. R&D in the context of nanoparticle use in the food processing industry is associated with the detection of spoilage and pathogens in the food as well as for sanitizing food processing equipment. Silver nanoparticles for instance are being incorporated in water filters for their action against bacteria. While these applications certainly have benefits, they could enhance the possibility of nanoparticle ingestion if these materials leach into food stuffs or filtered water. Food companies are also showing interest in research for the inclusion of nanoparticles in food stuffs to enhance nutrition or flavours.

The sphere of drug delivery is an area that is also being revolutionized by the application and use of nanoparticles (Salata, 2004; Singha and Lillard Jr, 2009). For example, the application of nanomaterials in this sphere is facilitating oral delivery of drugs that previously needed intravenous delivery. Other approaches that are using nanoparticles or nanocapsules to deliver drugs through the skin, lungs, stomach, and eyes are already being tested in clinical and pre-clinical trials. The potential advantages of these approaches are many and include increased solubility and resistance to gastric enzymes (offering oral delivery of drugs that previously needed intravenous delivery), controlled release, and the ability to direct the drug, by various means, to where it is needed. Therefore, the use of nanomaterials in pharmaceuticals presents an important route for human exposure.

Accidental consumption of nanoparticles is also a strong possibility in occupational set-ups, in case adequate measures providing sufficient protection are not taken. For example, chances of oral poisonings are possible from contamination of food or cigarettes from unwashed hands, or through accidental swallowing.

Information on the possible adverse effects caused by ingested nanoparticles is still being developed, although gastrointestinal absorption is anticipated. Some experts suggest that the presence of nanoparticles can cause Crohn's disease (Buzea et al., 2007), a chronic relapsing inflammatory bowel disease that is characterized by transmural inflammation anywhere in the gastrointestinal tract, where the immune system is triggered to attack the gut lining, causing it to ulcerate and break up. Dietary sources of nanoparticles (e.g., natural dietary contaminants, man-made food additives or pharmaceuticals) have been associated with the Crohn's disease (Lomer et al., 2002; Antonietta, 2004).

4.3.2 Potential toxicological implications of nanomaterials for human health

Studies on animal models and testing on human cell lines have shed light on the possible impact of nanomaterials on humans. As described previously, entry into the human body might occur by inhalation, dermal contact or ingestion, and intravenous application in case of drugs. Once inside the body they could imperceptibly enter organ systems, pass through cell membranes, and penetrate into the cell environment. The capacity for the unobtrusive transportation of nanomaterials within the body is explained by the similarity in their sizes to cellular components, which allows them to evade the natural defences that species have evolved to combat and remove foreign bodies. Therefore, in effect they might act as 'stealth particles' (Borm and Kreyling, 2004). This enables them to migrate within the human body, moving away from their initial site of deposition to accumulate even in other parts of the body and trigger a variety of reactions in these locations (Borm and Kreyling, 2004). In fact, the uptake of nanoparticles has been observed in several types of cells including pulmonary and alveolar (present in the lungs) cells, intestinal cells, and nerve cells. It has even been speculated that nanoparticles might be able to cross the blood brain barrier making it useful for drug delivery but requiring several safety evaluations (Hoet et al., 2004; De Jong and Borm, 2008). After entering the body, nanoparticles, due to their large surface area, could enable 'non-specific' absorption and binding to cellular components, triggering adverse reactions and leading to interference with important cell functions (Borm and Kreyling, 2004). Nanoparticles have been found to induce oxidative stress in organs such as the liver and lungs, which might result in the chronic depletion of anti-oxidant defences causing health problems (Hoet et al., 2004; Ahamed et al., 2011; Guan et al., 2012).

Research on the potential risks from various routes of exposure to nanoparticles has been undertaken. Specifically, research on the toxicological hazards of inhaled nanoparticles has gained from studies on particle toxicology and the effects of inhalation of fine particles (Borm and Kreyling, 2004; Donaldson and Poland, 2012). Inhalation of nanoparticles might result in several impacts ranging from inflammation of the respiratory system and tumor induction, cardiovascular diseases, etc. (Donaldson and Poland, 2012; Shvedova et al., 2008, Card et al., 2008). Nanoparticle inhalation is also speculated to increase the risk of adverse responses such as the impairment of lung function in persons already afflicted with lung disease, for example in asthmatics.

The potential capacity of nanoparticles to bind and react with cellular components has given rise to concern with respect to nanomaterial use in therapeutic applications. Use of nanoparticles for drug delivery can pose hazards that are unique and are beyond those experienced previously (De Jong and Borm, 2008). Nanoparticles, after the release of the intended carrier molecule could interact with other protein molecules, form complexes with them, triggering functional changes that lead to their malfunctioning (Borm and Kreyling, 2004). In addition, research has also revealed that since cells and organ receptors are sensitive to nanoparticles, they could interfere with signalling processes (Comfort et al., 2011; Brown et al., 2004), damage mitochondrial structures and the nucleus (Vandebriel and De Jong, 2012). Nanoparticles used in drug delivery systems must be biodegradable, soluble or else possess a molecular weight within a specified range, in the absence of which they could also persist and accumulate in the organs and cells in the body. Given the current gaps in the understanding of nanoparticle interaction with cells in organ systems, it is vital that adequate toxicological studies are conducted to determine the safety of the nanoparticles before they are used in food or drug applications, as these particles can enter the body from the intestinal tract (Hoet et al., 2004; De Jong and Borm, 2008).

Although several studies have indicated that nanomaterials can be hazardous to humans, there are other investigations that have demonstrated an absence of toxic impacts on nanomaterial exposure. For example, Stern and McNeil (2008) have reported that the lung, gastrointestinal tract, and skin act as significant barriers to the systemic exposure of many nanomaterials. Others (Nel et al., 2006) have also indicated that only a limited number of nanomaterials have demonstrated toxic effects in tissue culture and animal experiments and that too at high doses. Since the toxicological profile of nanomaterials would vary from case to case, data that emerges from studies on specific nanomaterials must not be generalized.

One of the reasons attributed to these contradictory opinions is the lack of standardized protocols for estimating the toxicity impact of nanoparticles. In their absence, scientists have adopted different experimental designs and methodologies to investigate similar research objectives, with contrary results at times. Still others argue that it is unclear if all nanomaterials are intrinsically toxic since the available testing methods are not adapted to nanomaterials and can thus produce false positive results (Krug et al., 2008b). In some cases, contaminants within the nanomaterials and the solvents used during the application have shown higher toxicity than the nanomaterials themselves. Therefore, it is crucial that in addition to standardizing toxicological assays, reference materials must be developed. Also results of nanomaterials cytotoxicity tests should also be correlated with at least two others in order to appropriately verify the results (Worle-Knirsch et al., 2006). Overall, considerable research needs to be undertaken to comprehend risks emerging from nanomaterials and there is a need to address several parameters such as accumulation, deposition, and kinetics in human and environmental systems.

4.3.3 Occupational health and safety issues in relation to nanomaterials

The vast expanse of R&D in the sphere of nanotechnology has led to the involvement of not only a large number of research laboratories in the design and synthesis of nanomaterials but also the participation of industry in manufacture of these materials. Hence, the workforce population in these organizations is likely to experience greater frequency or duration of exposures to nanomaterials. Currently, there is a lack of clarity on the nature of hazards and exposure levels at work places. Thresholds and guidelines, to limit exposures to nanomaterials are still being formulated. Given the size and properties of nanomaterials, it is uncertain if the prevalent industrial practices developed to avoid/mitigate exposures from existing chemicals are appropriate for curbing exposures to nanomaterials. It is also unclear if production facilities, especially in developing countries such as India, follow precautions adequately to minimize occupational exposures. For these reasons, the health and safety of the workforce involved in activities associated with the development of nanomaterials is of vital concern. At present the greatest risk appears to be to the health of the workers involved in the production, packaging or transport of the nanomaterials whereas inhalation of airborne nanoparticles is seen as the most common route of exposure at occupational set-ups.

It is possible that many researchers and industry workers are handling and producing nanomaterials without having enough information about the health risks (Maynard and Kuempel 2005; European Agency for Safety and Health at Work, 2012). Maynard et al. (2004) reported relatively low airborne mass concentrations of raw single walled carbon nanotube (SWCNT) in one facility, although concentrations increased considerably when the material was agitated. Similarly, studies by Lee et al. (2010) and the National Institute for Occupational Safety and Health (2010), also report the prevalence of carbon nanotubes at workplaces that could result in occupational exposures. In view of the potential toxicity of nanomaterials, there is concern about worker exposures to materials like carbon nanotubes. The review by National Institute for Occupational Safety and Health (2010) noted that studies (Shvedova et al., 2005; Muller et al., 2005) have reported 'an equal or greater potency of carbon nanotube in comparison to other inhaled particles known to be hazardous to exposed workers — ultrafine carbon black, crystalline silica, and asbestos — in causing adverse lung effects including pulmonary inflammation and fibrosis'. Other studies have implicated carbon nanotube exposure in rodents to pulmonary fibrosis and reduced lung clearance (Shvedova et al., 2005, 2008; Pauluhn 2010; Porter et al., 2010). Therefore, characterization of potential exposures of workers to the engineered nanoparticles as well as examining the possible impacts is crucial.

Another aspect associated with the production and storage of nanomaterials relates to their stability and the safety concerns they might pose at production facilities. In this context, it is likely that the physico-chemical characteristics of nanoparticles, such as small size and large surface area, could make some specific nanomaterials amenable to ignition (Pritchard, 2004; Holbrow et al., 2010). For example, nano-scale Al/MoO3 thermites ignite over 300 times faster than corresponding micrometer-scale material (Granier and Pantoya, 2004). Furthermore, while conductive nanopowders may not in themselves be an electrostatic hazard, they could penetrate into electrical and electronic equipment and give rise to short-circuit problems (Holbrow et al., 2010).

At present, the understanding of the occupational, health, and safety aspects of nanomaterials is still evolving. Recently however guidelines on the safe use and management of engineered nanomaterials at the work place have been developed by various agencies.[2] Experts also believe that options to minimize exposure and hazards could be guided by insights from ultrafine material toxicity (Yokel and MacPhail, 2011).

4.3.4 Pathways for environmental exposure

The release of nanomaterials into the environment — air, water, and soil — is possible during their manufacture, use, and disposal. Industrial effluents, waste waters, air-borne emissions, and solid-waste discharges generated during manufacture of nanomaterials or nanoproducts could lead to environmental contamination, especially if not treated appropriately. Unintentional releases could also occur from accidental spills and leaks during handling, storage and transport, especially since they are produced in bulk quantities in manufacturing units (Oberdorster et al., 2005; Ostiguy et al., 2009). Consumer usage of nanoproducts such as cosmetics, textiles, and disinfectants could also release nanoparticles into domestic waste waters (Daughton and Ternes, 1999; Brar et al., 2010) whereas their use in applications such as remediation and as pesticides could result in the direct introduction of nanomaterials in the environment. Experiments, such as washing of nanosilver socks, have revealed that nanosilver can be released from the textile matrix (Benn and Westeroff, 2008). The use of free nanoparticles for remediation is also being field-tested and sites have been

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[2] For example, see 'Standard Guide for Handling Unbound Engineered Nanoparticles in Occupational Settings', ASTM E2535-07; available at http://www.astm.org/Standards/E2535.htm or OSHA Fact Sheet, Working Safely with Nanomaterials, 2013. Available at http://www.osha.gov/Publications/OSHA_FS-36.pdf (last accessed: December 2013)

injected with various nanomaterials (Mace, 2006). Likewise nanoemulsions and nanoparticles of lanthanum-based compounds are being used in surface disinfectants and to prevent the growth of algae in pools and aquariums, increasing the possibility of these particles entering the drainage system. On the other hand, whereas disposal of industrial solid waste or nanoapplications containing nanomaterials — tyres, packaging materials, electronics, cells, filters, paints etc. — in landfills could cause discharges into surrounding soil or ground water, incinerating nanomaterial wastes could also generate airborne emissions. Since improper disposal of such wastes can pose serious threats to the environment, there is a need to develop a comprehensive approach to tackle this challenge (Oberdorster et al., 2005; European Commission DG ENV, 2011).

Studies indicate that nanomaterials might undergo different reactions in the environment such as aggregation, degradation or modification of surface coatings, and removal from embedded matrix resulting in free nanoparticles (Nowack and Bucheli, 2007). However, fate and behaviour of nanomaterials in the environment would depend on their physico-chemical properties as well as the conditions prevalent in the environment. These parameters would influence the likelihood and extent of nanomaterial transport through the environment (movement through water and soil, etc.) as well as their interactions with other substances in their surroundings. Research conducted on the transport of nanomaterials in porous media concluded that nanomaterial type, size, surface properties, and environmental factors (Nowack and Bucheli, 2007) influence transport processes.

4.3.5 Potential toxicological implications of nanomaterials for environmental species

Since most previous studies have concentrated on examining the impacts of nanomaterials on human health, fewer studies exist on the eco-toxic potential of nanoparticles. Nevertheless, in recent years, there is a growing volume of research in this sphere. Researchers are concerned that nanomaterials might be non-biodegradable and persist in the environment for long to form a new class of pollutant posing a novel threat to the environment — air, water, and soil — and human health (Reijnders, 2005; Werkema et al., 2010). The ability of nanoparticles to undergo biomagnification in food chains has also been speculated

(USEPA, 2007, Werlin et al., 2010). In addition, as nanomaterials possess increased reactivity due to their large surface area, they might act as vehicles enabling the transport of other chemicals and even pollutants. Essentially, nanoparticles can adsorb toxic compounds to either amplify or alleviate their toxicity. Amplification of the toxicity might occur due to synergistic effects between the nanoparticle and the compound. On the other hand, if the nanoparticle is non-toxic, the compounds' adsorption to the nanoparticle might serve to diminish its environmental concentration and bioavailability, consequently reducing its toxic impact (Nowack and Bucheli, 2007).

Studies have been carried out to analyse the toxicity of nanoparticles to various aquatic organisms. These studies have demonstrated that aquatic organisms can assimilate nanoparticles in their bodies which may then result in toxic responses in these organisms (Nowack and Bucheli, 2007). For example, carbon nanotubes have been found to elicit a toxic response in rainbow trout, especially in its respiratory system (Zhu et al. 2006a; Federici et al., 2007; Gagné et al., 2010, 2012) whereas in another study on embryos of zebra fish, carbon nanotubes were found to cause delayed hatching (Cheng and Cheng, 2005; Cheng et al., 2007; Huichin Pan et al., 2011). Oberdörster (2004) showed that the 48 hours LC50 in *Daphnia magna* for uncoated water-soluble fullerenes nC60 is 800 ppb which makes it moderately toxic. Furthermore, titanium dioxide nanoparticles were observed to be toxic to aquatic species whereas conventional titanium dioxide nanoparticles did not seem to cause adverse effects (Lovern and Klaper, 2006). Other studies have also noted that nanoparticles can be toxic to unicellular bacteria and protozoa apart from fish species (Nowack and Bucheli, 2007; Li et al., 2012; Wang et al., 2012).

In other research, the impact of nanomaterials on soil organisms, especially microorganisms, has been examined as these organisms are responsible for maintaining soil fertility and contribute significantly to the functioning of bio-geochemical cycles. Some of these studies have indicated that specific nanomaterials might affect microbial populations and diversity in soil (Bandyopadhyay et al., 2012). In experiments, it was noted that nanoparticles, such as C60, cesium dioxide nanoparticles, were adsorbed on bacterial cells (Lyon et al., 2005) while others like zinc oxide nanoparticles were internalized by bacteria (Brayner et al., 2006). Metal and metal oxide nanoparticles like those of silver, titanium dioxide, and silicon dioxide have also shown to elicit toxic effects in bacteria (Lok et al., 2006; Adams et al., 2006; Nogueira et al., 2012). On the other hand, fullerenes have demonstrated little impact on soil microbial populations (Tong et al., 2007) although bactericidal properties of fullerenes have also been reported (Yamakoshi et al., 2003). Studies also indicate that metal and metal oxide nanoparticles could interact with plant cells and can be taken up by plant systems (Nowak et al., 2006; Nowak and Bucheli, 2007; Priester et al., 2012). Research on plant systems indicate that while larger particles did not affect root growth in crops such as maize, cucumber, carrot, and soya, aluminium nanomaterials reduced root growth in the same (Yang and Watts, 2005). However, it was pointed out that the study did not take into account the fact that soluble Al+3 ion is root toxicant and that the solubility of aluminium oxide is known to increase with decreasing particle size (Murashov, 2006). Interaction of nanoparticles with plant systems can lead to plant growth inhibition, plant damage, and inhibition of nitrogen fixation, all of which pose risks to soil fertility and food supply. Therefore, it is essential to design nanoparticles that are minimally bioavailable and environmentally compatible as well as manage nanoparticle wastes so that they do not accumulate in soils (Priester et al., 2012).

As viewed from this last example, research undertaken in the area of environmental impacts of nanomaterials has been criticized on occasions for poor experimental design as well as for drawing incorrect conclusions. Other inconsistencies have also been observed. For instance, Oberdorster et al. (2004) exposed the juvenile largemouth bass fish species to different concentrations of fullerenes and observed that exposures to lower concentrations resulted in penetration of the blood–brain barrier, damage to both gills, and the brain. Unexpectedly however these effects were observed to be absent when the fish species were exposed to higher concentrations of fullerenes. In an experiment with another species (copepods), no effects were displayed when the test species were exposed to purified carbon nanotubes, however un-purified carbon nanotubes resulted in increased mortality (Templeton et al., 2006), indicating that contaminants and by-products co-present with nanomaterials might also induce ecotoxicity rather than the nanomaterial itself. In contrast, in a surprising observation in another study, the stimulation of growth in a unicellular protozoan was observed in the presence of carbon nanotube (Zhu et al., 2006b). Similarly, other research has revealed that when the seeds and leaves of the spinach plant were exposed to nano-sized titanium dioxide, a positive effect on the plants growth was observed.

Overall, there is insufficient data on the exposure and effects of nanoparticles on ecosystems (Colvin, 2003). Researchers have also cautioned that toxic effects observed in tests on environmental species could be a result of the elevated and unrealistic concentrations to which the test organisms have been exposed to and to which they would not be exposed to in real life conditions. Research in this area, while revealing much-needed information on the toxic potential of nanomaterials to environmental health, has also at times been plagued with contradictory or inconclusive studies (NanoFATE, 2010) and even poorly designed investigations (Clemente et al., 2012).

There is a need for a greater number of well-designed and focused studies to examine the environmental and human impacts of nanomaterials and to elucidate toxicity mechanisms. An area of research that might contribute in mitigating toxicity from nanomaterials is examining ways in which toxicity of these materials might be 'masked' via nanoengineering. It is well known that the physico-chemical properties of nanomaterials can be manipulated and customized through engineering to alter their functionality and even reduce potential toxicity effects. Cytotoxicity studies with quantum dots, for example, have demonstrated that the type of surface coating can have a significant effect on cell motility and viability (Lovric et al., 2005). In other examples, increasing the sidewall functionalization of SWCNT rendered these nanomaterials less cytotoxic to cells in culture (Sayes et al., 2006a) whereas differences in the phase composition of nanocrystalline structures have also been observed to influence cytotoxicity (Sayes et al., 2006b). Although greater research is needed in this area, these examples show that there might be ways to circumvent the environmental and health risks from nanomaterials while still enabling their use in applications.

4.4 Examining Environment and Health Issues of Nanotechnology in the Context of India: Case Study of a Nanosilver Application

Given the prospects that nanotechnology presents in the spheres of water treatment, renewable energy, drug delivery, and agricultural production, the potential of applying nanotechnology applications to advance the development agenda is gaining traction in developing countries, such as India. On the other hand, the growing evidence of hazards from certain nanomaterials makes it clear that the sustainable development of nanotechnologies will depend on the adequate understanding and management of potential concerns. Since it is imperative to avail opportunities and simultaneously govern risks, this presents a dilemma to all nations interested in tapping nanotechnology. However, this predicament is more acutely felt in developing countries such as India, where limited capacities and resources for addressing environment and health issues translates into prioritization of R&D and commercialization over adequate risk management.

Transformative, enabling, and socially embedded technologies, such as biotechnology and nanotechnology pose several daunting challenges to scientists and policy-makers. India could be more vulnerable to risk manifestation from nanotechnologies for several reasons including limited awareness and lagging response to potential risks, under-developed mechanisms for management of environmental health problems, and restricted capacities for regulatory implementation and oversight (Deshpande Sarma, 2011). Therefore, it is crucial that attention is paid to understanding the potential environment, health, and safety implications of nanoapplications that are commercialized or are nearing commercialization. Here, a case to case evaluation of the risks from nanoapplications that involves examining both exposures and hazard potential could help delineate and identify specific concerns. Developing comprehensive data on the magnitude of exposures and toxic potential of nanoapplications or nanomaterials is challenging in the present scenario. Nevertheless, utilization of life cycle approaches for understanding the risks from nanoproducts and processes producing or using nanomaterials could provide valuable insights (Som et al., 2009). Such techniques facilitate the evaluation of exposure scenarios and pathways along the manufacture, use, and disposal phase of the product. This knowledge can then be linked to the information on hazard potential for the nanomaterial utilized in the product for enabling at least a preliminary understanding of the safety issues involved with the nanoapplication.

There is a growing market for nanosilver applications in India. Nanosilver products that have been commercialized or are in advanced stages of product development include at least four kinds of products — water filters, fridges, washing machines, and health care products such bandage dressings and textiles (Deshpande Sarma, 2011). Among these products, water filters that incorporate nano-scale silver have received attention for their ability to ensure access to safe drinking water, the lack of which poses a significant development challenge to developing nations. In the absence of portable water, large sections of India's population are afflicted with waterborne disease-related morbidity, infant mortality, and adverse social impacts. Nanosilver is being utilized in water filters due to its effectiveness as an antibacterial agent, an ability that is attributed to its nano-scale size and higher reactivity. Nevertheless, although nanosilver use is gaining prominence for these reasons, there are also concerns regarding the safety of nanosilver products since it has been known to display some level of toxicity (Wijnhoven et al., 2009). For these reasons and also to extend the assessment of risks of nanosilver applications to specific cases, the possible environment and health issues related to the development and use of a nanosilver-based water filter were evaluated as a case study.

4.4.1 Exploring the environment and health issues around the development of a nanosilver-based candle filter

Environment and health issues linked to the nanosilver candle filter were examined by assessing exposure potential to silver content that may include nanosilver and reviewing the information available on the hazards of nanosilver. In order to understand the exposure scenarios the life cycle of the candle filter was considered in terms of the following stages:

- Incorporation of nanosilver in the ceramic candles. This involves the addition of silver nitrate into the ceramic candles followed by the dipping of candles in a reducing agent bath. Following this the candles are dried;
- Assembly and use of the candle filters by consumers; and
- Post-consumer waste management.

Overall, the study focused on those processes that were directly related to nano-scale silver and was not concerned with other aspects linked with the system. Therefore, potential impacts of other inputs (raw material and energy use) or outputs (other waterborne or airborne emissions not related to silver) that might be associated with the system were not considered in this study.

First, the potential for release of silver content was examined followed by the possible routes for human and environmental exposure.

4.4.1.1 Potential silver releases

The data inventory necessary for this analysis was compiled using interviews with technology developers and site visits. Detailed information on the production of the nanosilver candles was unobtainable as the product was being patented. Other data on the magnitude of releases was also not available.

Silver-related discharges are possible from the nanosilver candle filter at various stages along the life cycle of the candle filter. During manufacture, the discharges are likely to occur in the waste water and effluents as well as in the solid waste generated. Given the nature of the manufacturing process, airborne emissions are unlikely; however, they cannot be ruled out as aerosol formation could occur. Use of the candle filter demonstrated that silver is leached into the filtered drinking water, especially in the first 2–3 filtrations that the manufacturers have recommended be discarded. However, the technology developers have asserted that post these initial filtrations the concentration of silver leaching out of individual candles is below the accepted international thresholds for human exposure to silver from drinking water. Cleaning of the ceramic candle by placing it in boiling water is also to be avoided since accelerated leaching of silver has been observed under these conditions. Finally, even at the end of the life of the candle which is presumed to be a year after its use, the candle may still contain nanosilver. For post-consumer waste management, the manufacturers anticipate the collection of candles and recycling of the nanosilver that is left within the candle. This recycling process could create possibilities for the generation of silver containing wastes and emissions. On the other hand, disposal of the candles at landfills could also facilitate silver releases in the soil and in extreme even the ground water table. In contrast, if the candles are incinerated, then airborne emissions with silver could result.

4.4.1.2 Potential pathways for human and environmental exposures to silver content

Occupational exposures to silver discharges are possible in the manufacturing unit through dermal and inhalation routes, especially if precautions are not taken. Although inquiries at the unit suggested that protective gear is used during the incorporation of the nanosilver in the candle and its production, it is unclear if these are adequate to prevent exposures to nanosilver per se, although they may prevent routine exposures to silver compounds. Environment releases of silver content into waste water streams or land are also possible if mechanisms for treatment of effluents and solid waste are not put in place. At present, since the production of nanosilver candles is low, the effluents and slurry generated are in relatively lower quantities. These wastes are stored in drums for transport to a hazardous waste treatment facility. The manufacturers anticipate a waste water treatment facility at the unit when the production scales increase. However, the effectiveness of both, the proposed effluent treatment plant and the hazardous waste plant, will decide if environmental releases of silver or nanosilver can be avoided. Sludge from effluent treatment plants that receive silver load can harbour silver content. This remains an important pathway for environmental exposures since in India, sludge is invariably utilized as fertilizer in agricultural farms.

The main route for human exposure to silver content during consumer use is likely to be during consumption of filtered water that contains silver discharges. The magnitude of exposure will depend on the silver leaching from candles and the number of candles used in the water filter. Whether usage of the filtered water for cooking might transfer the silver into the food, making this another route of exposure through ingestion, needs to be examined. At present the technology developers claim that human exposure to silver content from water filtered using the candles is below that of the international threshold of 0.1 mg/L (defined by the WHO). Dermal exposure although minimal could result during handling of the filtered water. In case the cleaning of the candle in boiling water results in aerosol production, then inhalation exposures of silver could also be possible. Environmental releases from consumer use would primarily arise from household waste waters that may contain silver. However, this would depend on the presence and efficiency of facilities for waste water treatment to ensure removal of silver content before the waste water is discharged into aquatic bodies.

In case the recovery of nanosilver is undertaken, occupational exposures — dermal or inhalation — to silver may occur at the recovery unit. Handling of the candle per se by either those who collect the candles and the workers at the unit is not very likely to lead to dermal exposures as the quantity of the silver in the candle at the end of life is likely to be small and also below the surface of the candle. Environment releases from the recovery unit would again depend on the presence of adequate facilities to treat the effluents and waste. In case the candles are disposed in landfill sites or are incinerated, release of silver content into soil ecosystems or the atmosphere, respectively, might be possible.

4.4.1.3 Reviewing evidence of the toxic potential of nanosilver

Since nanosilver is incorporated in the candle filter and there is a possibility of human and environmental exposures of nanosilver along the life of the product, a brief review of the toxic potential of nanosilver is described in this section.

Evidence suggests that nanosilver could elicit toxic responses by a mechanism different from the kind elicited by silver and is likely to pose greater toxic potential (Navarro et al., 2008). Several investigations indicate that nanosilver could be toxic to humans, mammals, aquatic species, and soil microflora. Animal studies have demonstrated that nanosilver can accumulate in the body and organs of the mammalian species through various routes including inhalation, ingestion, and dermal contact (Wijnhoven et al., 2009). Adverse impacts of nanosilver on the functioning of different kinds of cells, organelles, and organ systems have been observed in dose response studies (USEPA, 2010). In vitro tests on human and mammalian cell lines also suggest that nanosilver presence can elicit toxic responses (USEPA, 2010). A case of silver poisoning by use of nanosilver dressings to treat burns has been reported. Here, the manifestations of silver poisoning were argyria — accumulation of silver in various parts of the body leading to bluish hue — tiredness, and loss of appetite (Trop et al., 2006). However, in contrast to the results of this study, other investigations on dermal exposures of silver or nanosilver have reported an minimal adverse effects or even beneficial effects in relation to wound healing (Supp et al., 2005; Wright et al., 2002). Repeated intake of colloidal silver, which contains nanosilver of various size distributions has resulted in argyria in humans and even death in the event of very acute exposures (Kim, 2009; Mirsattari et al., 2004).

In relation to environmental impacts, nano-scale silver has also found to be hazardous to species such as zebra fish, beneficial soil microbes, and nematodes. Nevertheless, there are questions on the bioavailability of nanosilver in environmental conditions which would impact the magnitude of exposures of environmental species to nanosilver. Concerns on the impact of nanosilver on efficiencies of waste water treatment systems have been raised given that nanosilver has been observed to disrupt microbial processes involved here (USEPA, 2010).

4.4.2 Evaluating concerns from the development of nanosilver applications: Implications for India

As seen in the above example, the development and use of the nanosilver candle filter presents possibilities for release of silver content as well as pathways for human and environmental exposures. In addition, reports on the toxicity of nanosilver suggest that exposure to nanosilver could elicit adverse responses in various species and even humans. For these reasons, despite the technology proponents' insistence of the absolute safety of nanosilver applications, it is important to analyse the basis for the environment and health concerns surrounding nanosilver applications, such as the candle filter.

One of the major concerns in relation to nanosilver applications is that the information that can inform society on the safety or risk of these applications is either still being researched, is unavailable or is being debated. In the case of the nanosilver candle filter, there are knowledge gaps that prevail at various levels making it difficult currently to arrive at an adequate understanding of the safety or otherwise the likelihood or extent of risk manifestation from the product. For one, the identity of the silver species in the potential releases is unknown — so it is not clear if these releases could contain silver ions, nanosilver or combinations of these species — although the nature of the hazards could be different for ions and nanosilver. Secondly, although it is possible to quantify total silver content in the potential releases, user friendly tools to identify and measure nanosilver concentrations in the releases are still under development or inaccessible, especially in developing countries. Since the magnitude of exposures to nanosilver is likely to influence the risk, this knowledge gap is critical.

If the releases are primarily silver ions, then much is known about risk issues. Silver itself displays considerable toxicity to environmental species, although manifestation of toxicity to humans has been observed only at exposures to large doses. Increased exposure to silver compounds has been known to result in argyria and is also connected to respiratory problems at occupational set-ups (Roseman et al., 1987). For these reasons, regulations for environment and health exposures to silver have been defined by some international agencies. Technology developers of the nanosilver ceramic candles claim that the silver releases in the filtered water are within the limits set by the WHO for human exposures to silver content. Therefore, provided the releases consist primarily of silver ions and as long as concentrations of silver in the releases in the drinking water do not exceed established thresholds, risks to consumers are likely to be negligible.

Besides consumer safety, occupational safety as well as environmental safety issues are also important considerations. Occupational health and safety national regulatory agencies, such as Occupational Safety and Health Agency (OSHA) in the US have described thresholds for air exposures to silver content. Other limits for silver content in freshwater have also been described by the United States Environmental Protection Agency (USEPA). However, whether such guidelines exist in the Indian context remains unclear. Moreover, even if they do exist, whether they are being adhered to and enforced remains a central question, given that regulatory oversight of environmental and health laws is weak in India (Deshpande Sarma, 2011).

In the case the releases are in the form of nanosilver, there are several uncertainties. There still does not seem to be a consensus on the likelihood or nature of potential hazards from nanosilver. Although on one hand there is growing evidence of toxicity from nanosilver, there are some other investigations that contradict these results. Again, industry representatives assert there has been long-standing use of colloidal silver and that exposures to colloidal silver have not resulted in adverse health impacts. However, opponents claim that silver in its nanoform is likely to pose new risks and point to evidence from toxicity studies. In this scenario, the absence of standardized methodologies for risk assessments of nanosilver has fuelled more confusion on the risk potential for nanosilver applications. Currently, besides the gaps on toxicity that still need to be bridged there are many unknown aspects about the fate, behaviour, transport and impact of nanosilver in the environment. Due to these knowledge gaps on the safety of nanosilver, regulatory decision on nanosilver use in applications is still awaited although several products using nanosilver have been commercialized. In the absence of standard regulations, the USEPA has initiated a registration review for nanosilver products. Under this review, all registrants are obligated to submit data on aspects, such as characteristics of silver incorporated in and released from the product followed by data on health and environmental impacts if deemed necessary. This is based on EPA's view that, 'the information required to assess the safety nanosilver is different from that of silver' (USEPA, 2012).

In developing nations environment and health problems are invariably marginalized in favour of technology development and industrialization. There is also a view that in countries such as India, there prevails an inadequate understanding of environmental problems and cumulative impacts as well as insufficient capacities for environmental management (World Bank, 2006). There has been a lack of focus in India towards developing an effective and coordinated effort for examining environment, health, and safety implications of nanoproducts, despite over a decade's engagement with nanoscience and technology (Deshpande Sarma, 2011). Support for risk research is fragmented and unsynchronized and lacks the breadth in terms of domain coverage. Furthermore, although nanotechnology research is expanding and nanomaterial-based products are being commercialized, there is delay in articulating adequate regulatory responses to nanotechnology. Although a number of nanosilver applications are in the Indian market, initiatives to assess potential exposure to nanosilver as well as environment and health and safety of these products in the Indian context is lacking.

In relation to nanosilver applications such as water filters, there are knowledge gaps with regards to the likelihood and extent of exposures to nanosilver. There appears to be growing evidence of toxic responses to nanosilver from laboratory research although there are still uncertainties on the extent of hazards in real world conditions. In this scenario therefore it is possible that the large-scale development and use of nano-scale silver applications, without adequate understanding of the potential environment and health implications as is the case today, might make India more vulnerable to potential safety risks.

4.5 Conclusions

Increases in nanomaterial production and wide applicability of nanoapplications could result in negative environmental and health consequences in the absence of adequate risk evaluations and management frameworks. Developing countries, such as India, are especially vulnerable to nanotechnology risks given the underdeveloped capacities to address potential environment and health concerns from nanotechnology's development and the inherent deficiencies that prevail in managing environmental health and safety challenges. What does this mean for developing countries who want to invest in nanotechnologies and develop applications which potential social and economic benefits? Risk refers to a probability, in effect an 'uncertain consequence derived of an event or activity with respect to something that is of human value' (Kates et al., 1985). India must initiate comprehensive efforts that can help anticipate, avoid and mitigate potential risks from the development of nanotechnology.

For this purpose, it is crucial that India initiate efforts to create a holistic and flexible strategy to identify and manage environment and health impacts from nanomaterial and nanoproducts to build resilience to potential risks. Clearly, dedicated funds for environmental, health, and safety research as well as risk management must be demarcated. Risk evaluations of commercialized or soon to be commercialized nanoproducts are imperative. Targeted research to fill knowledge gaps in risk assessments is necessary to inform regulatory decision making as are stakeholder consultations when scientific uncertainty on risks is apparent. There is also an urgent need for establishing appropriate occupational health and safety measures for ensuring safety at research and production facilities. Rapid advances in the technical, regulatory, and policy domains are being achieved at global platforms to address nanotechnology risks. India must participate effectively at global discourses to build capacity in governing risks and place forth its viewpoint as a developing country. Adequate consideration and initiatives to manage potential environmental and health impacts would facilitate the safe development of nanotechnologies and also help India reap the benefits in a sustainable fashion.

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CHAPTER 5

Prospective Socio-economic Implications of Nanotechnology for Commodity-dependent Countries: An Exploratory Case Scenario*

Shilpanjali Deshpande Sarma and Anandajit Goswami

5.1 Introduction

History of technology development shows that technological innovation presents opportunities as well as challenges to society. The Industrial Revolution that was founded on technological innovation propelled advancements in various sectors such as manufacturing and agriculture leading to social change (Deane, 1965). While industrial progress did bring enormous positive transformations in the economies of nations, it is also likely that certain sections of the society may not have gained from the resulting shifts experienced during that time. For example, rapid industrialization and utilization of machines in the textile industry did result in the loss of livelihoods for weavers. The development of synthetic dyes in Europe also led to the drop in demand and loss of exports for natural dyes that were being produced and exported on a large scale by countries such as Turkey, Mexico,

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Liberia, and India (The South Centre, 2005; Headrick, 1998; Martin-Leake, 1975; Buttel et al., 1984). Communities affected from these shifts include the people engaged in indigo plantation in India who suffered losses in employment and income due to the resulting drop in the cultivation of the indigo crop (Headrick, 1998). Technological innovation has also been cited as one of the reasons behind a fall in demand for labour during the Great Depression which resulted in a reduced demand for goods (The South Centre, 2005).

Currently, society is witnessing rapid development, adoption, and diffusion of sophisticated technologies. Therefore, while on one hand, we welcome these technologies inspired by the opportunities and benefits they can bestow on us, there is also a need for introspection on the potential socio-economic challenges that might accompany revolutionary technologies. Since industrialization and technological innovation could result in commodity substitution and upset commodity-based livelihoods, the current work uses this lens to undertake an exploratory exercise for examining the potential socio-economic implications of a transformational and promising technology, i.e., nanotechnology, specifically in context of commodity-dependent nations.[1] This chapter seeks to assess both potential concerns and the possible advantages nanotechnologies could pose to the utilization of some existing commodities as well as countries that rely on trade of these commodities.

5.2 Nanotechnology and Commodity-dependent Countries: Exploring Issues and Implications

Nanotechnology comprises a range of technologies that are derived from the design, production, and application of nano-scale materials with the aim to develop novel or enhanced products and processes. Nanotechnologies can contribute to various sectors ranging from manufacturing, chemical engineering, information technologies to pharmaceuticals, renewable energy and others. Given the enabling nature and breadth of the sectors it can assist, nanotechnology has been described as being revolutionary, i.e., it can provide opportunities for enhancing industrial competitiveness and

[1] Potential issues with regard to environmental and health implications, regulatory challenges, and ethical concerns in relation to nanotechnology are covered in other chapters of this book.

improving socio-economic conditions of developed and developing nations. Nevertheless, despite its potential for ample benefits, the inherent complexity and transforming nature of nanotechnology creates uncertainties in terms of the repercussions its development can have on the environment, health, socio- economic, and ethical domains.

Today, nanotechnology has shown promise in terms of its wide-ranging application in various industrial domains ranging from consumer goods, pharmaceuticals, electronics, food and beverages, etc. While product development and markets appear to be primarily concentrated in the developed world, developing countries are also beginning to engage in the manufacture and commercialization of nanomaterial-based products. Given the pace of research and development (R&D) and breadth of applications, nanomaterials are likely to be applied in a number of sectors for developing applications with novel functionalities and enhanced performance.

In light of the transformational potential of nanotechnologies in markets, businesses, and global economy, there has been speculation on its impact on existing commodity trade and commodity-dependent nations. The term 'commodities' comprises 'undifferentiated raw materials that are widely traded' (e.g., agricultural products, metals, and minerals) in the global market (Meridian Institute, 2007), in large volumes on the basis of price (O'Herron, 1999). Nations, whose major exports comprise one to three commodities, are considered as commodity-dependent countries (Meridian Institute, 2007). Primarily encompassing developing, least developed nations (Meridian Institute, 2007) as well as indebted poor nations, commodity-dependent countries possess significant commodity resources and are therefore suppliers of these resources to global markets. Commodity trade is intrinsically linked to economies of these countries, the export incomes contributing to state revenues and Gross Domestic Product (GDP). The economic sustenance of these nations revolves around future projections of global commodity demand which prompts investment and activity in the commodity sector for production and export. Commodity trade is also the source of livelihoods of the peoples of these nations and therefore is linked to the social welfare of the country. In the light of these issues, there has been discussion on the potential positive and negative implications of the development of nanomaterials or nanomaterial-aided applications on the economic and social structures of countries reliant on commodity trade and exports.

Some researchers have alleged the possibility of nanotechnologies substituting the use of agricultural or mineral commodities in specific sectors (Meridian Institute, 2007). In this eventuality, there is a risk of a drop in demand of commodities which could negatively affect commodity-dependent countries relying on commodity exports for their socio-economic sustenance. On the other hand, nanotechnology is believed to provide numerous opportunities to developing nations in relation to addressing development-related problems (Salamenco-Buentello et al., 2005). In relation to commodities, nanotechnologies might, for example, facilitate an increase in their demand by either enhancing the value or utilization potential of the commodity (Meridian Institute, 2007; Jones, 2004).

5.3 Possibilities for Nanotechnology-aided Substitution or Value Enhancement of Commodities

The concerns regarding the ability of nanotechnologies to displace traditional commodities has been raised previously. At the North–South Dialogue on Nanotechnology, Mosibudi Mangena, South Africa's Minister of Science and Technology, stated that increased investment, research, and innovation in nanotechnology could result in cheaper, functionally rich, and stronger materials that could threaten most traditional materials.[2] This section highlights specific commodities that could be impacted by current advancements in the nanotechnology domain. Possibilities of commodity substitution as well as value enhancement of commodities by nanotechnologies are identified.

Cotton: Cotton fibre already faces competition from synthetic fibre. Thus, emergence of nanoengineered fabrics that substitute cotton use could be a cause for concern for the cotton industry. On the other hand, nanotechnology is also providing avenues for value enhancement of cotton products. For example, addition of nanosilver during the manufacturing of cotton fabrics endows these fabrics with novel functionalities and potential advantages

[2] South African Government Information, 2005. Opening address by the Minister of Science and Technology, Mr Mosibudi Mangena, at the Project AuTEK progress report function, at Cape Town International Convention Centre, Cape Town. http://www.info.gov.za/speeches/2005/05020812451001.htm (last accessed: April 2013).

during use. Research has shown that nanosilver or nanomaterial-enhanced cotton fabrics can possess antimicrobial and anti-wrinkle properties (Phong and Thanh, 2009; Wasif and Laga, 2009) as well as exhibit improved durability (Jeong and Bae, 2009; Avila, 2008; *Science Daily*, 2010). Nanotrade Ltd., a Czech company already sells nanosilver garments (t-shirts, socks, underwear) with the claim that the fabric can "conduct sweat away from the skin" and eliminate odour.[3] Commercialization of such nanomaterial-aided cotton textiles could help maintain the demand and trade for cotton.

Rubber: In the rubber industry, longer lasting tyres are being made from aerogels in place of rubber. Aerogels comprise a matrix of nano-sized particles of silica and plastic that have air bubbles trapped in them. They are being used as a replacement for rubber for their ability to enable lighter and long-lasting tyres (American Chemical Society, 2002). A technology called Zyvex Molecularly Engineered Rubber (ZyMER) exists which uses a new chemical process to allow carbon nanotubes to be inserted into synthetic rubber compounds to enhance the mechanical and electrical properties of the material without sacrificing elasticity (*Industry Week*, 2012). Such advances may lead to increased sale of synthetic rubber products which are already replacing utilization of natural rubber. Alternatively nanomaterials might also be utilized to enhance the properties of rubber (Noguchi et al., 2005; NanoProducts, 2003a) to yield safer and more durable tyres. Nano-scale fillers such as carbon black and silica, which account for approximately 30% of tyre mixtures, are essentially used to impart rubber with properties such as grip, abrasion resistance, and wear and tear propagation resistance (Nanostart, 2012). Such nanomaterial-aided improvements of rubber could sustain the demand for natural rubber.

Metals and minerals: Nanomaterials with their increased surface areas and unique properties are being considered as replacements for mineral commodities such as copper and platinum in specific sectoral applications. As large-scale manufacture of nanomaterials becomes a reality, their application in the manufacturing industry could permit higher efficiencies and cost reductions in technological processes. For instance, nanomaterials are

[3] Nanotrade Ltd, 2012. Available at http://www.nanosilver.eu/ (last accessed: February 2013).

currently being considered for substituting use of platinum in the fuel cells (Baker III, 2005; *Fuel Cell Industry Report*, 2005). Quantum Sphere Inc. (2005) has developed a nano-nickel/cobalt alloy to replace the use of platinum catalysts in hydrogen fuel cells. Nano Stellar Inc.'s nanoparticles that combine precious metal with other less costly metals (PCAST, 2005) could also substitute the application of platinum. While Quantum Sphere has applied for three broad patents for its nano-scale nickel, Nano Stellar Inc. is preparing patents for its low-cost nanocatalysts (NanoProducts, 2003b). Platinum has great demand in the automotive, battery and fuel cell industry as a catalyst (The South Centre, 2005; QuantumSphere Inc., 2005). High price of platinum coupled with its limited reserves hold huge importance for developing countries that earn revenues from platinum trade. Reduced demand for platinum in industry could adversely affect countries dependent on platinum exports.

Alternatively, there is also interest to utilize nanotechnology to enhance the value of metal commodities. For example, the South African government launched 'Project Autek' which explores avenues for developing 'new industrial uses' for gold, (which is the country's largest generator of export earnings) in order to offset a potential loss in markets (International Centre for Science and High Technology, 2005; ETC Group, 2008)

5.4 Potential Socio-economic Impacts for Commodity-dependent Countries from Nanotechnology Developments

5.4.1 Potential repercussions from nanotechnology-aided commodity substitution

Rapid advances in R&D are being experienced in the public and private domains of nanotechnology in developed and developing nations such as India, China, Brazil, and South Africa. Compared to the developed world, commodity-dependent nations, which include developing and least developed countries, might lack resources for engaging with nanotechnology development. These countries have also demonstrated relatively lower participation in the debates on societal implications of nanotechnology. Past experiences demonstrate that commodity-dependent communities are vulnerable because livelihoods of their communities could be displaced by technology induced shifts in commodity trade. Therefore, countries that rely extensively on commodity trade could also be vulnerable to socio-economic crises and poverty in case they experience a drop in commodity exports and prices.

The global market value of cotton is US$ 67,186 million[4] and approximately 6 million people are engaged in cotton production in West and Central Africa (UNCTAD, 2005). Therefore, any drop in demand for cotton would severely affect countries such as Burkina Faso, where 35 per cent of GDP comes from the cotton sector.[5] Countries such as Thailand, Malaysia, Indonesia, and Sri Lanka are some of the world's largest producers and exporters of natural rubber. Lowered demand for rubber could adversely impact these nations. Similarly, decreased trade in platinum could negatively impact the mining and quarrying sectors of countries such as South Africa and Zimbabwe that are amongst the largest producers and exporters of platinum.

The United Nations Conference on Trade and Development (UNCTAD) analysis in 2002 showed that three commodities accounted for half of the gross export earnings for 46 developing countries illustrating the dependence of many developing countries on commodity-based export earnings (UNCTAD, 2002). UNCTAD (2005) also shows that there is a positive correlation between commodity dependence[6] and the Human Development Index indicating the association of commodity export earnings and development indicators. Therefore, a possible shock to commodity trade, such as a reduced demand or price volatility arising from technological advances that displace commodity use in various applications, could hurt commodity-dependent countries. On one hand, the drop in commodity exports would affect the GDP of commodity-dependent countries given that their economies are fuelled largely by commodity export earnings. On the other hand, this environment could lead to negative social ramifications such as the loss of employment and diminished incomes for communities that are dependent on the commodity sector for their livelihoods. These impacts could result in a rise in the prevalence of poverty, inequality, and fall in human welfare as well as

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[4] Cotton Outlook, 2012. Available at http://www.cotlook.com/userfiles/file/SpecialFeatures/2012/LongstapleSF_2012_Web.pdf (last accessed: February 2013).

[5] Cotton Made in Africa, 2013. Available at http://www.cotton-made-in-africa.com/en/the-initiative/where-we-work/burkina-faso.html (last accessed: February 2013).

[6] Commodity dependence is defined as when more than 30% of the export earning of the country comes from the export of commodities.

quality of life in commodity-dependent countries that are already burdened with development challenges.

5.4.2 Potential opportunities from nanotechnology-aided value enhancement of commodities

Nanotechnology-aided transformations of commodities might permit a continuing or increased global demand for commodities by way of novel or improved uses for the commodity. It may also facilitate new export markets given that the commodity might be traded with countries that have invested in nanotechnologies and are interested in developing nanotechnology-based products. Such opportunities would spell potential benefits for commodity-dependent nations. Furthermore, the prospects for enabling nanomaterial-enhanced commodity goods might provide commodity-dependent countries the incentive to engage and develop nanotechnology capabilities. This would in turn provide opportunity for these countries to innovate and use nanotechnologies in ways that can enhance the value of their indigenous commodities thereby finding new markets.

5.5 Case Study on the Copper Sector

Given the potential socio-economic significance of nanotechnology for developing and least developed countries reliant on commodity exports, a critical assessment of the opportunities and impacts nanotechnologies pose to specific commodities may be useful. An understanding of commodity applications that nanotechnologies may potentially supplant could provide an understanding of the nature and extent of the threat nanotechnology poses to commodity demand and commodity-dependent countries. Conversely, examining the enhanced value that nanotechnologies could impart to commodities could stimulate an awareness in commodity dependent countries on such likely opportunities.

Copper is a widely utilized and traded commodity (Figure 5.1); its production and consumption is experiencing a continuous increase since the mid-20th century. Average demand for refined copper has grown at a compound growth rate of 13.24 per cent from 1998–99 up until 2008–09, with a growth elasticity of 1.13 per cent (IMACS, 2010[7]). The major sectors that utilize refined copper

[7] Estimations are based on the data obtained from IMACS, August 2010, and the Indian Copper Industry, ICRA Management Consulting Services Limited, New Delhi.

are the building and construction sector as well as the electrical and electronic products industry, as seen across Asia, the US, and Europe (Figures 5.2, 5.3, and 5.4). In the electric and electronic sector, copper cables and wires are employed to develop power cables, building wiring, magnet wire, automobile wire and cable, appliance wire, electronic interconnections, etc. While on one hand the demand for copper appears robust, there is evidence of the development of nanotechnology-aided applications that might have the potential to dislocate copper use in specific sectors. Some of these applications are in the process of being commercialized or have entered the market. Alternatively, R&D has also emerged on the ways in which copper use can be enhanced by nanotechnologies.

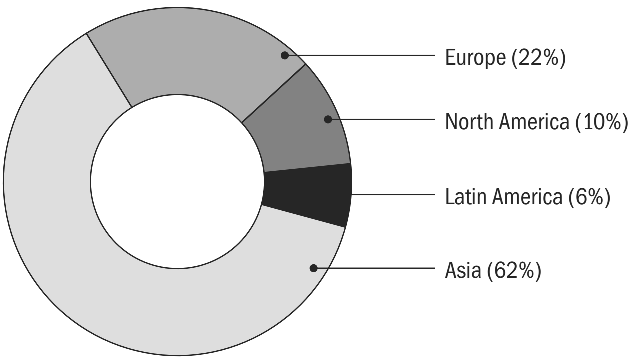

Figure 5.1: Copper usage by region, 2010
Source: ICSG (2012)

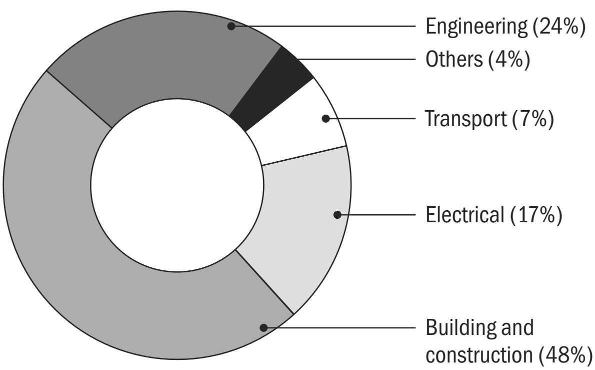

Figure 5.2: Sector-wise usage of copper in Asia, 2007
Source: Mansukh Investment and Trading Solutions (2007)

With this background, this section first identifies and examines the scope of nanotechnology applications that may substitute or diminish copper utilization in various sectors. Potential time scales for commercialization of these specific nanotechnology applications are explored along with the challenges. Following this, the potential of nanotechnology applications to influence the demand of copper is examined, based on the understanding of consumption patterns of this metal. Likely socio-economic implications of this scenario are assessed for two countries, Chile and Zambia, that

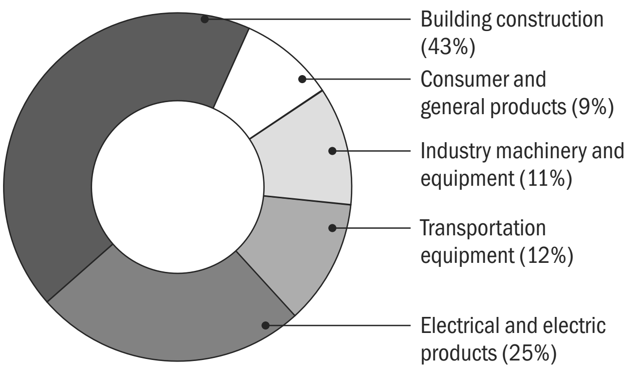

Figure 5.3: Sector-wise usage of copper in the US, 2007
Source: Mansukh Investment and Trading Solutions (2007)

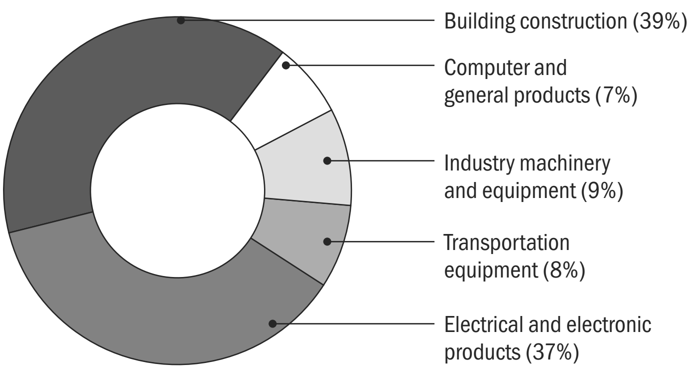

Figure 5.4: Sector-wise usage of copper in Europe, 2007
Source: Mansukh Investment and Trading Solutions (2007)

are significantly dependent on copper exports. Opportunities that nanotechnology can pose for value addition of copper are also ascertained.

5.5.1 Nanotechnology-aided applications with a potential to substitute copper use

5.5.1.1 Scope of replacement of copper in power transmission

Copper wires are routinely employed for power transmission and distribution in many countries, especially developing nations. Since copper-based transmission lines result in 7 per cent loss of power and energy, alternative methods for power transmission are being explored. The idea of nanomaterial-based power cables, superconductors, has been contemplated for rewiring electricity grids. In this case the nanotechnology power cables would replace the use of copper and aluminium wires in the grid. Nanomaterial-based cables could facilitate power transmission along long distances enabling continental and international energy transport as well as minimize thermal sag failures and other technical losses experienced in traditional wiring systems (Adams and Jaffe, 2007). Nanomaterial-aided technologies for power transmission include Second Generation High Temperature Superconducting (2G HTS) wire and carbon nanotube quantum wire-based systems.

High temperature superconducting wire

First Generation HTS (1G HTS) wires are currently being utilized for underground power generation and are being considered for overhead applications in the future (Lawrence Jr. et al., 2002). Although they are not nanotechnology aided, they have greater power carrying capacity than copper wires; each 1G HTS wire can replace approximately nine copper wires although small quantities of copper is utilized in their core structure and shielding (Malozemoff, 2007; McCall and Lindsay, 2008). Already in use in some developed nations (Lawrence Jr. et al., 2002; The Energy Blog, 2007; Eckroad 2006; Azomaterials, 2009), the technical, environmental benefits envisaged by the use of 1G HTS (Lawrence Jr. et al., 2002; The Energy Blog, 2007; Azomaterials, 2009; Das 2006) are convincing experts in developing nations that 1G HTS may be an ideal choice for replacing copper wires in countries such as India and China (Elcock, 2007; Chinese Academy of Science, 2006). For these reasons it is anticipated that the HTS cable industry would grow to be a multimillion dollar industry by 2020 (ORNL, 1998).

Recently, in order to improve the efficiencies of 1G HTS wire, changes at the nano-scale are being introduced at the manufacturing process stage to develop 2G HTS wires. Inclusion of nanoparticles in the structure of the wire enhances the capacity and ampacity of the HTS wire preventing energy losses (Hessian Ministry, 2008). Fujikura, a Japanese company, has been involved in manufacturing long HTS wires with critical current densities greater than 3,000,000 A/cm^2 and production rates of 10–100 m/h for quite some time now.[8] Companies such as American Superconductor (AMSC) assert that their 2G HTS wires are "smaller, lighter and more cost effective than comparable systems based on copper wire" (American Superconductor, 2004). Experts also allege that a single 2G HTS wire could conduct as much current as 100 copper wires and power about a thousand homes (Gizmag, 2006). Nanodots in the superconductor coating of the AMSC wires facilitate increased current flows despite high temperatures and strong magnetic fields (American Superconductor, 2004) responsible for reduced efficiency in 1G HTS wires (Elcock, 2007). 2G HTS wires also provide five-fold cost benefits over that of 1G HTS wires (Sarrao and Kwok, 2006). Price declines have been experienced with increased gross production capacity (Haught, 2007). Altogether, there is a possibility that with the rising prices of copper, HTS costs could compete with that of copper, making HTS cables as an attractive option for commercial use (Elcock, 2007).

There has been much interest in 2G HTS applications given the ability of superconductivity applications to alleviate exceedingly congested power grids and also because the price performance ratio of 2G HTS wires is predicted to be equivalent to copper in the future (Gizmag, 2006). HTS technology has been emphasized amongst the technologies in the G-8's Energy Security Plan developed for constructing superior power networks (Gizmag, 2006). Applications for the 2G HTS wire include power transmission, propulsion motors and generators, degaussing cables, synchronous condensers, and fault current limiters (*Superconductor Week*, 2008). Transition from 1G HTS to 2G HTS has been initiated (Sytnikov et al., 2008) and markets anticipated for 1G HTS are likely to adopt 2G HTS (Selvamanickam et al., 2008). Companies are already manufacturing 2G HTS in design and volume so as to

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8 Fujikura, 2011. Available at http://www.fujikura.co.uk/products/plant-and-infrastructure/superconductors/#productDescription (last accessed: February 2013).

replace 1G HTS wires (American Superconductors 2G HTS, 2011; Gizmag, 2006; Superpower Inc., 2011; Selvamanickam et al., 2008). Demonstration projects utilizing 2G HTS wires are underway (Bob Lawrence and Associates, 2008; The Energy Blog, 2007; Meridian Institute, 2007). Nexans, a Europe-based cable provider that has more than 10 years of experience with superconducting cable wires recently completed testing of 2G HTS wire samples manufactured by Superconductor Technologies Inc. The wire met Nexans' critical limit for HTS AC power cable applications by carrying greater than 500 Amps of current per centimetre width at 77 Kelvin. Spokesperson at Superconductor Technology Inc. said that the success of these tests indicates that they are on the right track to fulfil future demands for cable transmission projects (*Reuters*, 2012). Based on these facts, a growth in demand for 2G wire could be anticipated in regions that either have on-going HTS projects and those that are looking to apply this technology. Overall, the rapid developments in this arena together with the advantages of HTS technology suggest that wherever feasible this technological application is likely to be considered as a substitute to copper cables in some countries in the near future.

Carbon nanotube quantum wire-based systems

The utilization of carbon nanotubes in power transmission as replacement of copper is being explored. Carbon nanotubes demonstrate higher electrical conductivity than copper wires (Davis, 2006; Elcock, 2007) and also possess high tensile strength, elasticity, and flexibility opening possibilities for weaving these nanotubes into 'quantum wires and cables' (Elcock, 2007). In fact, experts allege that a 1-metre-long quantum wire prototype might possess a 10 times higher capacity to conduct electricity (Rice University, 2005). Quantum wires are likely to be stronger, lighter, and adapt to temperature fluctuations displaying higher conductivities and lowered resistance (Elcock, 2007; Baker III, 2005; Hoffert, 2004). For this reason, they could enable greater distances between towers (Baker III, 2005; Hoffert, 2004).

Development of a carbon nanotube wire has been commissioned at the Rice University (Rice University, 2005). Nevertheless, despite some optimistic views about the deployment of this technology from researchers and government officials, several challenges lie in the path of quantum wires becoming feasible and commercially viable. Firstly, current synthesis methods for carbon nanotubes usually deliver only minute volume of quantum wire appropriate configurations. Additionally, sorting the appropriate quantum wire configured nanotubes from other configurations is extremely difficult (Elcock, 2007). At present, despite being manufactured in some developed nations (Nano Werk, 2011), carbon nanotubes are produced in low volumes at very high costs. There are also challenges with manipulating nanotubes into long wires due to which the prototypes being developed are generally of short length (in centimetres) (Elcock, 2007). In view of these issues, it appears that quantum wire technology still needs to mature, the advancements being dependent on technological breakthroughs to help overcome the aforementioned challenges (Davis, 2006). Developing approaches for reliable, efficient, cost effective, and large-scale manufacturing capacities of quantum wire appropriate carbon nanotubes is the first step towards carbon nanotube quantum wire development.

The feasibility of the development and deployment of quantum wire technology for power transmission could probably emerge as a long-term possibility (Hessian Ministry, 2008) implying that carbon nanotube-based quantum wires are unlikely to replace copper power lines in the near future (Hessian Ministry, 2008). In contrast to quantum wire-based power lines, the nanotechnology-enabled 2G HTS cables appear to be a closer commercial prospect. Due to their proven technical benefits and commercial feasibility they might be a more efficient alternative to copper-based transmission lines. These incentives, along with copper's rising prices, might make the adoption of HTS cable, a competitive alternative in several countries which might have traditionally used copper for power transmission.

5.5.1.2 Scope of replacement of copper in magnet wire applications

Besides power transmission, HTS wires could be utilized to improve the efficiency of motors, transformers, magnets, and generators. Copper wires are routinely used in electrical magnets in the industry and military. Since HTS wires enable 'higher power densities and reduced losses' when compared to copper-based systems (NESPA, 2009), smaller, lighter, more efficient, and durable magnets could be developed that deliver better performance with lower operating and maintenance costs (American Superconductor, 2011). Manufacturers have developed commercial HTS magnets and they are being used in scientific and military spheres (American Superconductor, 2011).

Spokespersons of HTS-110, a New Zealand-based company, claim that 2G HTS wire could be a potential substitute to copper in several specialist applications due to the cost effectiveness of this technology (HTS-110 Magnetic Solutions, 2009a). Whereas copper-substituting HTS products are being developed for magnets, industrial generators, and motors (Industrial Res. Ltd., 2006), other emerging markets include the domains of scientific instrumentation, marine motors, and industrial processing (Industrial Res. Ltd., 2009; Industrial Res. Ltd., 2006). HTS-110, envisages a niche area for New Zealand in a global industry if the price of HTS wires drops, since the technology is competitive and is also experiencing a strong demand (HTS-110 Magnetic Solutions, 2009b). The successful commercialization and proliferation of this HTS magnet technology could induce the replacement of copper wires in the area of magnets and industrial motors. In October 2011, Superpower Inc. started their new programme named ARPA-E REACT Program to develop a low-cost wire for HTS wind turbine generators (Superpower Inc., 2011) in support of their other wire development efforts.

5.5.1.3 Scope of replacement of copper in the interconnects application of the electronics sector

Copper wires are utilized as interconnects in electronic chips to facilitate the routing of electric power and signals. Presently, a constant demand for smaller and faster chips at the nanometer process (Hamada et al., 2005; Naeemi and Meindl, 2005) has prompted the need for copper-based interconnects in smaller dimensions. However, at such small dimensions, copper interconnects are not only expensive and difficult to fabricate but they also exhibit electric and structural breakdowns, leading to performance losses and circuit malfunctions (Morral et al., 2005). Since the interconnect problem has been identified as one of the major roadblocks in the way of future chip fabrication (Arrowhead Research Corporation, 2005), researchers and manufacturers need to locate replacements for copper to enable chip sizes smaller than the 45 nm node (Hamada et al., 2005; Naeemi and Meindl, 2005). This has led researchers to explore the utilization of nanomaterials such as nanotubes in semiconductors replacing the use of copper (Kreupl et al., 2004).

Nanotubes can carry up to a billion amps per square centimetre. They also display substantially lower resistance compared to copper and are stable at the required dimensions (Morral et al., 2005; Collins and Avouris, 2000; Kreupl et al., 2004; Naeemi et al., 2005). Studies demonstrate that nanotubes could exhibit low resistances and greater efficiencies than can copper interconnects (Morral et al., 2005; Collins and Avouris, 2000; Kreupl et al., 2004; Naeemi et al., 2005). Therefore, replacing copper with nanotube interconnects could result in faster and more efficient computers, improved wireless network, and cellular phone systems. Research on these aspects is currently on-going (University of California, 2005). Researchers and industry have demonstrated a keen interest in carbon nanotube interconnects (Hamada et al., 2005) and have experimented with these interconnects with some success (*The Hindu*, 2003; Naeemi and Meindl, 2005; Kreupl et al., 2002). Scientists have demonstrated that carbon nanotubes can route electrical signals faster than traditional copper (Azonano, 2005) and have 'developed both high speed nanotube interconnect technology and high speed nanotube transistor technology, [that] they hope to integrate [in] an ultra-high speed all nanotube electronic circuit' (Azonano, 2005).

Yet, there are challenges in the path to developing and demonstrating a mature semiconductor prototype that incorporates carbon nanotube interconnects. These include synthesis of desired quantities, qualities and configuration of carbon nanotubes, integration of carbon nanotubes in chips, and changes in chip design to suit carbon nanotubes (Morral et al., 2005). Researchers have considered a post growth processing approach to enable carbon nanotube interconnect semiconductor technology (Morral et al., 2005). In this approach, carbon nanotubes already synthesized, purified, and packed in bundles are then placed onto the chip at appropriate positions. However, researchers will need to develop new and specialized tools that allow for positioning of the bundles of carbon nanotubes (Morral et al., 2005).

Despite these challenges, the pace at which R&D appears to unfold in this area leads us to speculate that carbon nanotube interconnect based technology might mature and become feasible in forthcoming years. Several companies such as Intel, Motorola, and Infenion have shown a strong interest in carbon nanotube interconnect based technology and have invested in R&D in this area (Nanotech, 2006). For instance, researchers at Smolket are attempting to integrate carbon nanostructures into existing Complementary Metal Oxide Semiconductor (CMOS) technology (Arrowhead Research Corporation, 2005). Compared to today's copper interconnects, the Smolket method facilitates much faster data transfer rates, demonstrates low-power consumption, diminished hardware strain, and also employs less complex process steps than do existing manufacturing processes (Arrowhead Research Corporation, 2005). Experts also believe that while carbon nanotube interconnects might not be suitable for replacing copper in logic or memory devices, their application might be possible in flexible electronic displays and photovoltaics (NIST, 2011). In the event that such technologies, reach maturity nanotube technology that delivers better performance than that of copper interconnects could replace the utilization of copper in semiconductor applications.

5.5.1.4 Scope of replacement of copper in the telecom sector

Copper cables are still utilized in the telecom sector in developing countries such as India and China, although copper use poses disadvantages of low resistance and moisture sensitivity that affects cable properties and performance (US Patent No. 7,162,137, 2001; US Patent No. 7,162,138, 2005). Optic fibre cables offer strong competition to copper (Liu, 2008) but high costs and durability issues have impeded its large-scale adoption (Infinite Cables, 2012). Therefore, recently there has been a focus on utilizing nanomaterials in the domain of optics cables and devices to help overcome these deficiencies and improve performance. Application of nanomaterials would increase the fibre's resistance to water and corrosion, provide flexibility, durability, and enhance efficiency and service life (US Patent No. 7,162,137, 2001; US Patent No. 7,162,138, 2005; *China Chem. Reporter*, 2001). These potential advantages have generated interest in the application of nanotechnologies in optics from both the academia and industry (US Patent No. 7,162,137, filed in 2001; US Patent No. 7,162,138, filed in 2005). Researchers are developing nanophotonic devices that will enable high rates of data transmission needed in the global fibre optical transmission systems (Ohtsu Research Group, 2009). Pirelli Labs, on the other hand, has focused on creating nanotechnology-based optical devices which could facilitate reduced size and power consumption making them suitable for large volume applications (Pirelli Group, 2009). Such developments could help expand the breadth of optics' application, enabling their use for purposes other than just long-distance network and high-capacity applications to which they are currently limited (since the optic cables are bulky and expensive). In this way, nanotechnology could facilitate the proliferation of this optics technology which could result in increased substitution of copper cable in the telecom sector (Pirelli Group, 2009).

5.5.2 Nanotechnology-aided interventions with a potential to enhance copper use

Nanotechnology could provide avenues for synthesizing and identifying unique functionalities of copper at the nano-scale. This could provide opportunities to harness properties of copper nanoparticles to develop novel applications or enhance existing products. Much R&D is underway in this sphere. Copper nanoparticles could be utilized as antimicrobials, fungicide, and algaecide (Dresher, 2006; British Patent No. 392556, 1931) as well as in lubricants, inks, coatings, polymers, plastics, and in some alloy and catalyst applications (Dresher, 2006; US Patent No. 3953658, 1972; Davis, 2001). Their ability to act as drug delivery agents for cancer therapies is also being explored. Copper nanorods may be employed as catalysts, in magnetic recording and magnetic resonance imaging (MRI).[9]

Researchers are also focusing on developing ways to use copper to control infections at hospitals and the food industry (Dresher, 2006; Copper Dev. Association, 2009; 2007). Experiments with nano copper solutions on cotton fabric demonstrated that nano copper treatments yielded improvement in antimicrobial efficiency and tensile strength of the fabric (Chattopadhyay and Patel, 2010). Furthermore, nano copper/polyimide composites might find application in microelectronics (Sullivan et al., 2005). Copper-containing organic–inorganic nanocomposites could also be employed for sorbing and retrieving radioactive cesium (Dresher, 2006). Usage of copper containing organic–inorganic nanocomposites that contain nano-sized copper ferrocyanide complex can facilitate the retrieval of cesium from nuclear waste in a manner that is clinically beneficial. This not only assists medical science but also beneficial for the environment (Dresher, 2006).

In Japan, researchers have created a hybrid copper-organic nanostructure that can preferentially sorb acetylene over carbon dioxide enabling their separation although these substances share closely related molecular structures (Dresher, 2006; Freemantle, 2005; Matsuda et al., 2005). Similarly, researchers at the US Department of Energy's Argonne National Laboratory are researching copper nanoparticle incorporating metal nanofluids for their ability to enhance heat transfer characteristics and improve efficiencies in automobiles, heating/air-condition systems, and industrial equipment (US Patent No. 6,221,275, filed in 1998). Though copper nanoparticles display a reduction in metal strength at the nano level (Dresher, 2006; Schiøtz et al., 1998), researchers at Johns Hopkins University developed a method to produce copper sheets with nanocrystallites that demonstrate strength,

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9 American Elements, 2013. Available at http://www.americanelements.com/nanotechnology (last accessed: February 2013).

ductility, and unusual stress–strain characteristics. Research is also on-going on the fabrication of copper phthalocyanine (CuPc) nanowires that might provide avenues for its use in organic electronic applications (Wang et al., 2010). These and other investigations on copper nanoparticles and their possible utilization could lead to novel applications in the future.

In addition to ongoing research, copper nanomaterials such as nanopowders, nanoparticles, and nanorods are currently also being sold in the market. Applied Nanotech Inc. has commercialized copper nanoparticles for application in various spheres such as conductive coatings, catalysts, and conductive inks and pastes. The company has also commercialized the nano copper ink technology as a replacement for standard silver- and gold-based inks in the printed electronics industry for its low cost and technical advantages. This technology is also licensed to Ishihara Chemical Company in Japan (Applied Nanotech Holdings Inc., 2011).

Aside from copper nanoparticles, researchers are applying nanotechnology towards maintaining copper products. For instance, nanocomposites of diamond are being utilized to enhance the wear resistance of copper alloy injection moulds (Armoloy of Western Pennsylvania Inc., 2009; Engelmann and Dealey, 2000; Engelmann et al., 2002; Narayan et al., 2005).

5.5.3 Examining the potential impact of nanotechnology-aided applications on copper demand

Nanotechnology applications present prospects for copper substitution in the domains of power transmission lines, magnetic wire, semiconductor interconnects, and telecom lines. These applications can however be broadly categorized as: (*i*) those that, at their core, are based on other technologies but incorporate nanomaterials to aid performance improvements (e.g., 2G HTS cables) and (*ii*) those that are based either entirely or largely on nanomaterials and nanoengineering at the nano-scale; e.g., carbon nanotube-based power transmission and carbon nanotube interconnects enabling enhanced functionalities (Deshpande Sarma and Chaudhury, 2009).

Applications developed from nanotechnologies such as 2G HTS cables appear to be closer to successful maturity and deployment. Field demonstrations of HTS technologies are currently ongoing in various developed and even developing countries such as China. Firms have also initiated manufacturing facilities for large-scale development of 2G

HTS technology. Therefore, although not perceived as a quintessential nanotechnology breakthrough, 2G HTS technology with its advantages could hasten substitution of copper use in power cables and magnet wire applications. If 2G HTS is adopted widely, a future drop in demand for copper might emerge with a potential to adversely affect copper exports of copper-dependent countries. Nevertheless, despite the potential of each HTS wire to replace several copper wires, HTS wires still incorporate some percentage of copper in its structure. Therefore, the extent of the drop in copper demand on its wider global application would need to be ascertained (Deshpande Sarma and Chaudhury, 2009).

On the other hand, the carbon nanotube-based power line application is more or less entirely nanomaterial and nanoengineering based. Successful development of this application is dependent on adequate availability and quality of nanotubes as well as significant advances in the engineering at the nano-scale. In both cases, it appears that several challenges need to be overcome to facilitate prototype development and successful commercialization of this technology. Given current uncertainities, development and deployment of carbon nanotube power lines could at most be considered a long-term possibility. Therefore, this potential technology is unlikely to affect copper demand in the power sector in the near future (Deshpande Sarma and Chaudhury, 2009).

In a similar vein, the application of carbon nanotube interconnects in semiconductors is also in development, although the R&D appears more advanced than the carbon nanotube power line technology. Currently, the technology is not yet ready for full-scale commercialization since it is dependent on developing capacities for the manufacture of carbon nanotubes as well as utilization of carbon nanotube inter-connects, deployment, and adoption of carbon nanotubes on a large scale. Therefore, the replacement of copper interconnects with carbon nanotubes in semiconductors is likely to be a future prospect. Carbon nanotube interconnect technology could have an impact on copper demand in the future however only if technology breakthroughs emerge and large-scale substitution of copper materializes.

Much like the 2G HTS technology, nanotechnology is enabling the enhancement of performance and durability of optics in the telecom sector. Nevertheless, copper use in the telecom sector is already under threat and has reduced due to the application of substitutes such as optic fibre and wireless technology (Henderson, 2012). Therefore, while nanotechnology applications might not be directly responsible for copper substitution in this sector, the increased efficiencies of nanomaterial supplemented optic fibre technology can facilitate and hasten the expansion of optic fibre usage globally and further lower the demand for copper in this sector (Deshpande Sarma and Chaudhury, 2009).

Currently, developing economies such as China and India are fuelling the demand for copper by way of the growing consumption in these countries in the power, telecommunication, and electronics sectors, among others (China Mining, 2008; Iyengar, 2008; Hindustan Copper Ltd., 2008). This has resulted in the emergence of China and India as important destinations of copper export for major copper exporting countries such as Zambia and Chile.[10] Therefore, a drop in the utilization of copper in the power, telecommunication, and electronics sectors due to nanotechnology interventions especially in China and India, could impact the demand for copper at the global levels. Nevertheless, besides applications in power, electronic goods, and telecom sectors, global copper demand is also influenced by copper consumption in sectors such as building and construction, heavy machinery, and transportation. In these sectors, presently, there does not appear to be any evidence of copper replacement by nanomaterial-aided applications or nanotechnologies. Since the overall demand of copper is derived from consumption in various sectors, it is possible that any future drop in demand for copper in the power, telecommunications or electronics sector could be buffered by demand for copper in the other sectors, especially if an increase in copper utilization is experienced in sectors such as building and construction, and others.

Besides enabling applications that can substitute copper use, research at the nano-scale on copper has opened up potentially new avenues for application of copper nanoparticles in various spheres. This is based on the unique or improved functionalities these substances can possess at that scale. Copper nanoparticles are also being manufactured commercially although the volumes are not as large as conventional chemicals. Whereas few copper nanoparticle-

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[10] Government of India, Department of Commerce, 2013. Available at http://commerce.nic.in/eidb/Default.asp (last accessed: May 2009); and International Trade Centre: Countries 2013. Available at http://www.intracen.org/menus/countries.htm (last accessed: May 2009).

based applications such as ink, etc., have already been commercialized, several potential uses are still in the R&D phase. Presently, copper nanoparticles are made from copper salts that form a small percentage of copper usage and demand. Therefore, currently the production of copper nanoparticles is unlikely to have much impact on copper demand. Nevertheless if large-scale application of copper nanoparticles is experienced in the future, the creation of additional markets for copper could perhaps influence and increase demand.

Overall, the likelihood of nanotechnology-aided applications amending copper use and changing copper demand depends on various aspects that must be viewed in an integrated manner. Nanotechnology-aided substitution of copper use may be experienced within the electrical and industrial machinery sectors in the future. On the other hand application of copper nanoparticles which represents nanotechnology aided enhancement of copper use is emerging but is unlikely to influence global copper demand at present. In order to predict if nanotechnology-aided interventions can influence copper demand, an understanding of *(i)* the commercialization and adoption potential of copper-use substituting or copper-use enhancing nanotechnologies as well as *(ii)* sector-wise copper consumption patterns and trends is essential. Here, it is important to keep in mind that adequate R&D investment, timely technological innovation at both the nanomaterial and nanoengineering scales and competitive pricing of these technologies will influence successful commercialization of both copper-use substituting or copper-use enhancing nanotechnologies. Furthermore, the overall

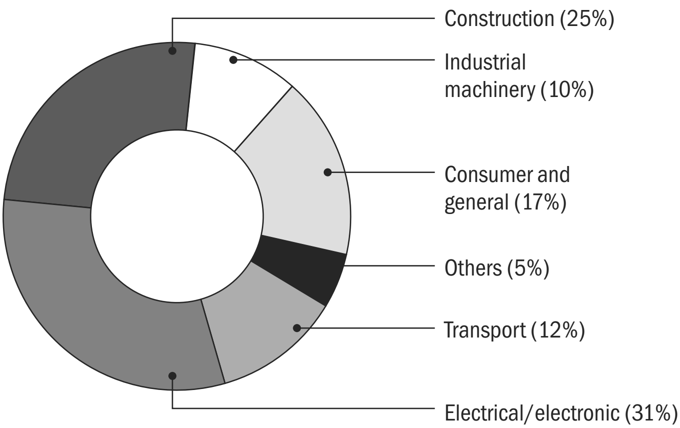

Figure 5.5: Sector-wise use of copper across the world, 2011
Source: London Metal Exchange (2013)

demand for copper is generated by its consumption across several other sectors, (Figure 5.5) including those where substitution by nanotechnology-aided interventions does not hold relevance at present. It is possible that an increase in demand could be observed in these sectors in the future. Focus on these dimensions is essential for discerning the patterns of copper demand and understanding the impacts of technological interventions.

5.5.4 Potential socio-economic implications of lowered copper demand on Chile and Zambia

In this section, copper-dependent countries Chile and Zambia, have been chosen to explore the possible socio-economic implications of reduced copper demand in the potential scenario that nanotechnology-led copper substitution occurs. Chile and Zambia rank first and seventh in the world for copper mine production and second and tenth, respectively, in refined copper production (ICSG, 2012; Edelstein, 2013). Furthermore, CODELCO, a state-owned mining enterprise in Chile is the world's largest copper-producing company with reserves for 200 years (US Dept of State, 2009). CODELCO is responsible for 53.5% of copper-mining investment that happens within the copper mining sector of Chile and further it plans to invest US$ 3.5 billion every year over the next six years during 2012 (E&MJ, 2012).

In both countries, copper makes up the largest share of the countries' exports. In 2010, Chile was the largest exporter of refined copper followed by Zambia (ICSG, 2012). In 2011, copper constituted 55% of Chile's total exports.[11] Zambia's copper exports also rose from 52% of its total export in 2002 to 69% in 2006.[12] In 2011, copper contributed to 78% of Zambia's total exports (Mobbs, 2012). Exports from copper trade for Chile were valued at $4.44 billion in 2012 (Market Watch, 2012). For Zambia, the exports were valued at $6.9 billion for the year 2011 (Mobbs, 2012). The contribution of copper export in Chile's GDP has increased from 7.26% in 2002 to 14.96% in 2006 with an exponential annual average growth rate of 1.20%.[13] In 2011, the share of

[11] Banco Espirito Santo Research Sectorial, 2012. Available at http://www.bes.pt/sitebes/cms.aspx?plg=1e3dd96b-ab68-4fe3-8141-03363ece66c0 (last accessed: February 2013).

[12] International Trade Centre: Countries, 2013. Available at http://www.intracen.org/menus/countries.htm (last accessed: May 2009).

[13] See website of International Trade Centre: Countries, 2013.

copper exports in the country's GDP increased to 18%.[14] The share of copper exports in Zambia's GDP increased from 12.94% in 2002 to 24.30% in 2006 with an annual average growth rate of 1.17%.[15]

Given that copper is the most exported commodity in both countries, in case nanotechnology-led copper substitutions are experienced in great volumes in the future, the drop in copper demand could result in a fall in exports of copper from Chile and Zambia. For instance, in 2010, most of the export earnings of Chile from copper came from export destinations at Asia, followed by China, the EU, and Japan. Miniscule export earnings to the tune of 0.20% and 0.10% came from Brazil and the US (ICSG, 2012) (Figure 5.6). Like China, India with its increasing copper consumption capacity, is also emerging as an important export destination of refined copper products. One of the major uses of copper in China, India, and Japan is for power transmission. However, both Asian and European nations have a keen interest in HTS applications and HTS cables for power application (Hawsey et al., 2006; Silberglitt et al., 2002; American Superconductor Corporation, 1997). Some of these countries that have taken up HTS demonstration projects are contemplating replacing their underground cables with HTS technology (Eck, 2009). In case these countries adopt 1G HTS and 2G HTS technologies, a drop

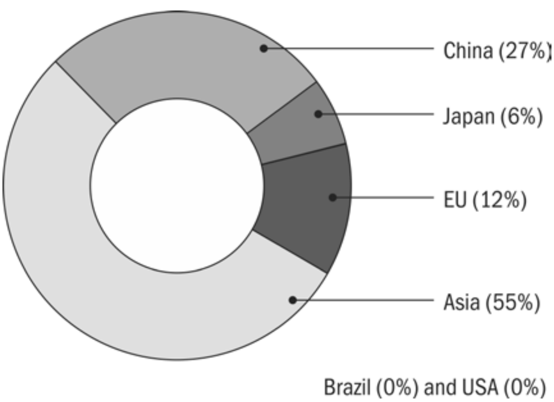

Figure 5.6: Distribution of Chile's export to various destination in 2010
Source: Estimated from Chile—EU, statistical indicators and trade figures, 2011 (ICSG, 2012)

[14] See website of Banco Espirito Santo Research Sectorial, 2012.
[15] See website of International Trade Centre: Countries, 2013.

in the demand for copper in the power sector might jeopardize a share of Chile's copper exports to these nations.

For copper-dependent countries such as Chile and Zambia, a decrease in copper exports could have repercussions in terms of diminished export earnings, loss in state revenues, and lowered GDP. Zambia could be more vulnerable to these impacts given that copper exports form a considerable share of Zambia's total exports, contributing significantly to its export value and overall GDP. Based on UNCTAD's analysis of country classification on the nature of commodity export (UNCTAD, 2002), Chile could be classified as a 'Diversified Commodity Exporter' (Gijón-Spalla, 2010) whereas Zambia might at present be categorized as a 'Transitory Non-Diversified Commodity Exporter' (Lusakatimes, 2010) (See Box 5.1). Moreover, while for Chile copper export destinations are more diversified, the bulk of Zambia's copper is exported to Switzerland followed by China (Miningmx, 2012) (Figure 5.7), making it more vulnerable to impacts if these two countries adopt HTS technology more widely.

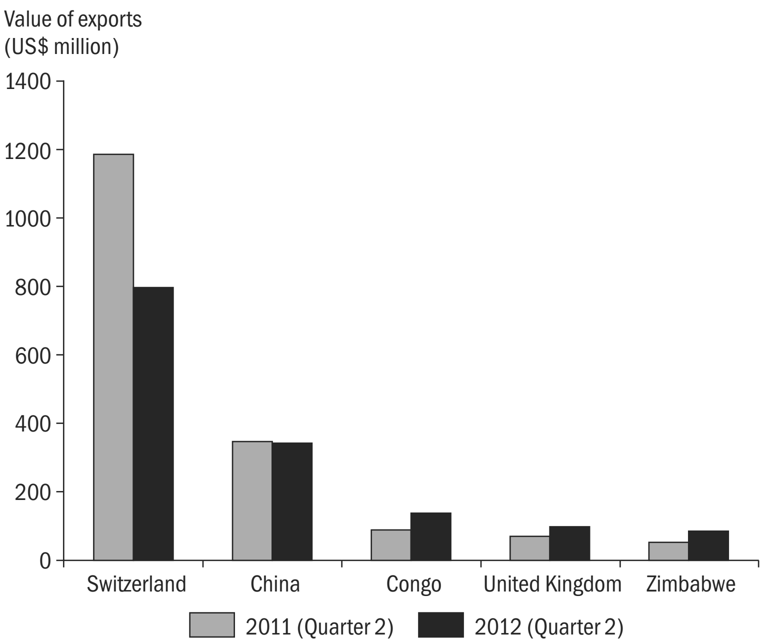

Figure 5.7: Zambia's major export markets
Source: Adapted from Central Statistical Office, Zambia, Direction of Trade Report, 2012 (Second Quarter 2012)

BOX 5.1: Country classification based on the nature of commodity export

Based on the nature of commodity dependence, countries of the world could be classified into the following categories: (i) Perennial Non-diversified Commodity Exporters, (ii) Transitory Non-diversified Commodity Exporters, (iii) Successful Non-diversified Commodity Exporters, and iv) Diversified Commodity Exporters.

'Perennial Non-diversified Commodity Exporters' includes least developed countries (LDCs) and small island states with large share of total export earnings coming from one or two commodities. These countries because of small geographical area and population are not able to move out of their dependence on these commodities. So, the socioeconomic risks due to fluctuating market changes impacting commodity exports are larger for these countries.

Transitory Non-diversified Commodity Exporters includes mainly African LDCs and non-LDCs. Countries in this category are also dependent on couple of commodities. But, these countries could diversify into alternative areas of commodity production and exports with a larger focus on high valued agricultural commodities.

Successful Non-diversified Commodity Exporters includes countries that are solely dependent on one or two commodities for their export earnings. Usually, these are small economies and remain exposed to external shocks resulting from changed market conditions for their commodities which can have a dramatic effect on their economy.

Diversified Commodity Exporters includes countries of Asia and Latin America whose economies and development are less exposed to shocks of the commodity markets arising from a market change. This is because the earnings for economic growth are dependent on various sectors apart from the commodities. But, sections of rural population in this category of countries rely on commodity production and exports for their livelihoods. Any shocks in the commodity market would impact these sections to a larger extent within the economy of these countries. However, socioeconomic risks due to shocks in commodity exports owing to change in market conditions are the least for Diversified Commodity Exporters amongst all the above-mentioned categories of commodity exporters.

Source: UNCTAD (2002)

In addition to potential economic impacts, these countries could also experience social ramifications. In both Chile and Zambia, the mining sector is an important source of employment. In 2012, the mining industry contributed to more than 20% of Chile's GDP which is equivalent to US$40 billion (E&MJ, 2012). The mining sector has generated a direct and indirect employment of almost 110,000 and 500,000 people. In Zambia, since 2010, there is a trend of a weakening mining sector with a 2.2 per cent reduction in the mining output (African Economic Outlook, 2012). The mining and quarrying sector contribution to GDP has reduced from 4.5 per cent in 2006 to 3.8 per cent in 2010 alongside the contribution of manufacturing sector which has dropped from 11.2 per cent in 2006 to 9.1 per cent in 2010. Nevertheless, the Zambian copper sector is still the largest employment generating sector outside any public service sector within Zambia. The copper sector of Zambia has created

20,000 jobs since 2009 till 2012.[16] Therefore, any drop in copper demand or exports is likely to adversely affect employment in the copper mining sector with ramifications for community livelihoods and human welfare in both nations. Here again, since Zambia is positioned low on the Human Development Index and is categorized as a heavily indebted poor nation burdened by high poverty and international debt, it could be more vulnerable than Chile to the potentially adverse social impacts that can emerge from a potential drop in copper export.

5.5.5 Emerging opportunities for Chile and Zambia from nanotechnology

Nanotechnology has generated significant interest in developed and even developing nations due to its potential socio-economic benefits of its application. However a North–South divide can emerge between developed nations that demonstrate cutting-edge R&D and patent generation in the nanotechnology domain and commodity-dependent nations that are resource rich but exhibit a lag in developing nanotechnologies or participating in the relevant discourses on nanotechnology and development.

Nanotechnologies, besides providing development opportunities for sectors as varied as health, water, energy, information communications, electronics, textiles, and others could also aid commodity-dependent countries enhance the value of their resources as long as appropriate capacities are developed for this purpose. As discussed in Section 5.5.2, R&D at the nano-scale in relation to copper has yielded several potential applications in various sectors ranging from medicine, inks, paints, polymers, etc. Manufacturing of copper nanoparticles is also an emerging industry. For these reasons, investment and involvement in nanotechnology especially in relation to copper could prove advantageous for Chile and Zambia. Alternatively use of nanotechnologies in the copper mining sector to improve copper production efficiencies could also be explored.

Both Chile and Zambia appear to have an interest in nanotechnology development. Chile has various research groups involved in nanotechnology

[16] The Bureau Investigates, 2012. Available at http://www.thebureauinvestigates.com/2012/06/15/scratching-the-surface-are-zambians-about-to-get-their-dues-from-foreign-miners/ (last accessed: February 2013).

R&D that receive funding from state programs (Scholze, 2007; Foladori and Fuentes, 2007). Research specific to copper in the nanotechnology domain includes:

- Production of copper nanoparticles for high conductivity polymers at the Universidad de Chile;
- Investigations on the electrical conductivity in thin films of copper at the Pontificia Universidad Catolica of Chile;
- Production of copper nanoparticles for industry for their use in the energy sector; and
- Research on nanocrystalline microstructural evolution occurring during the processes of mechanic alloying and consolidation of copper-based powders (Zumelzu, 2006).

There is an interest in Chile to utilize nanotechnology to develop and commercialize technologies that harness the states' copper resources (Foladori and Fuentes, 2007). CODELCO has also keen interest in developing nanotechnologies for its application in the copper mining industry. It is focusing on developing human resources in this domain (Bühlmann, 2004). This provides opportunities for collaboration between academia and industry in Chile.

Zambia has initiatives in nanotechnology although its activities and investments in this domain appear to be of a lesser degree in comparison to Chile's initiative. Zambia is a member of NANOafnet, which seeks to involve researchers in Africa in nanoscience and technology (Msezane, 2006). At the National University of Zambia, researchers are investigating the properties of titanium nanoparticles for its application in solar cells (NANOsciences Africa Network, 2008). Thus, there exists potential for Zambia to extend its research on metallic nanoparticles to copper as well.

The advancement of nanoscience and nanotechnology in developing nations is challenging given the imperatives for monetary resources, sophisticated infrastructure and skilled manpower for effective engagement in this field. Nevertheless, Chile and Zambia have already undertaken some initiatives to promote nanotechnology in their countries. Despite the fledgling nature of their engagement in this domain, the sustainable expansion of nanotechnology development may prove beneficial for Chile and Zambia given the potential development opportunities the technology presents. Furthermore, harnessing nanotechnology's potential to enhance the value of their natural resources and sustainably developing its mining industry could also provide socio-economic benefits. Here extending the application of nanointerventions to the copper sector for developing copper nanoparticles would probably open up new markets and opportunities for trade in the future.

5.6 Conclusions and Options for a Way Forward

Commodity-dependent countries rely significantly on commodity trade and export revenues for socio-economic sustenance. In many cases, development initiatives both in the economic and social sectors in these countries are proposed and planned based on revenues anticipated from commodity trade. Therefore, unforeseen shocks to global commodity demand can leave commodity-dependent nations vulnerable to negative repercussions owing to such changes. On the other hand, identifying new opportunities for commodity utilization and increased commodity trade can support the economy of commodity-dependent nations.

Emerging technologies like nanotechnologies have the potential to alter and raise efficiencies in a wide breadth of sectors, even those that currently rely on commodities. In case of commodities such as metals, nanomaterial-aided technologies could possibly substitute use of platinum or copper in specific applications in the future. Alternatively, manipulations at the nano-scale can open up opportunities for manufacture of nano-sized metal particles with unique properties that might facilitate enhanced or novel applications.

There appears to be growing evidence of the development of nanotechnology-aided applications that can substitute copper use in certain spheres. Copper use in the power transmission could face competition from 2G HTS technologies that incorporate nanomaterials and can potentially replace nine copper wires per HTS wire. HTS wires could also substitute copper use in magnet wire applications. Quintessential nanotechnology-based breakthroughs such as quantum wire based power lines and nanotube interconnects are also being explored as substitutes for copper use for power transmission and in the semiconductor industry respectively. However these applications are currently still confined to the R&D stage, their commercialization dependent on technological capacities and breakthroughs. On the other hand the development of copper nanoparticles can facilitate new uses for copper, although at present, markets for copper nanoparticles are small and potential applications are still being researched.

Several factors must be taken into consideration while anticipating the impact of nanotechnology developments on the copper sector and demand. This includes the feasibility of the development of copper substituting or copper use enhancing nanotechnologies and their commercial viability. Examining or forecasting the interest and demand for these sophisticated technologies at a global level is also essential. One needs to keep in mind that the demand for copper is generated by its use in a range of sectors whereas the impact of nanotechnologies on copper demand is probably limited to select sectors. Copper substituting nanotechnologies for instance might be able to influence a potential drop in demand for copper in power transmission and magnet wire applications in the future. However, copper demand also emerges from consumption in other sector such as building and construction, transportation and others where substitution by nanotechnology-aided interventions does not hold relevance at present. On the other hand copper use enhancing nanointerventions such as nanoparticles are derived from copper salts that presently contribute to a very small share of the global copper demand. Therefore, besides assessing technological drivers, it is essential to understand sectoral and overall copper consumption patterns, for estimating the impacts of nanotechnologies on copper demand.

Copper-dependent countries such as Chile and Zambia could be impacted by both the development of copper use substituting as well as copper use enhancing nanotechnologies. A potential drop in copper prices or demand could lead to fall in export revenues, reduced growth rates, particularly for Zambia whose copper exports form a significant proportion of its export basket. Social ramifications may include loss of livelihoods or income for persons involved in the copper sector. Alternatively, nanotechnology could also open up opportunities for these countries for enhancing the value of commodities like copper and identifying new markets based on potential applications. Here, Chile does appear to have initiated R&D to explore properties and potential applications of copper nanoparticles. Nanotechnology could additionally be harnessed to develop applications that benefit other sectors such as mining, manufacturing, health, water, energy, etc. This, however, necessitates greater engagement of these countries with R&D and innovation in nanotechnology.

Whereas the development of nanotechnology in Chile and Zambia could provide prospects for socio-economic growth, there is also a need to explore approaches for mitigating the vulnerability of such commodity- dependent nations to a potential fall in copper trade in the case of widespread adoption of copper substituting nanotechnologies. Such approaches could include diversification of the country's export basket (to reduce dependence on single commodities) as well as diversification of export destinations for the major exported commodity. Designing effective industrial, trade and labour policies to mitigate the potential negative ramifications of commodity substitution would also be crucial. Research and forecasting mechanisms are also needed to facilitate an understanding of future trends in relation to commodity consumption patterns as well as potential technology-based commodity substitutions or enhancements. This could help conceive country-specific plans of action in advance. Efforts in this line could help reduce the vulnerabilities of commodity dependent nations to any potential adverse repercussions from nanotechnology aided commodity substitutions. It could also help commodity dependent countries identify suitable opportunities for harnessing nanotechnologies for the purpose of adding value to indigenous commodities.

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CHAPTER 6

Socio-ethical Risks in Nanotechnology

Subhasis Sahoo and Manish Anand

6.1 Introduction

Growth of technology is no doubt a reflection of human creativity; it has helped generations to survive and improve the quality of their lives through the control of nature. This control, while no doubt, often meant destruction and domination of other species, has also helped save other species at times. Technological innovation brings excitement in some quarters, but anxiety in others, particularly ethical and social issues. Given the variety of benefits promised by nanotechnology in agribusiness, energy, environment, health, information technology (IT), and medicine, we have also one or more of the following possibilities: (*i*) immense gain for mankind at large, but raising major ethical concerns; (*ii*) intra-country exploitation through unethical practices, thus underscoring the need for the country to have appropriate regulatory mechanisms; (*iii*) inter-country exploitation which encourages and propagates neo-colonialism and neo-liberalism; and (*iv*) explicit and manifest damage to human beings and to the environment.

Genuine fear of genetically modified (GM) crops arising from relatively less studied science combined with the fear of the unknown and lack of transparency of the companies dealing with GM crops made most governments and their citizens in the developed countries oppose the technology. Fearing that nanotechnology, another transformative technology, may face the same fate, the UK Royal Society had published a detailed report on nanotechnology in 2004. The report, very much available in the public domain was published well before the larger society had formed an opinion. It had listed out both the risk(s) and benefit(s) of the technology and the areas that still needed more investigation.

6.2 Ethics and Nanotechnology

We believe that philosophy and ethics have a critical function in the implementation of new technologies. According to Andrew Feenberg, there has been a surfeit of the essentialist philosophy of technology and we need to question concepts like technological imperative, instrumental rationality, efficiency, etc. Technological essentialism, he believes, is born out of a loss of distinction between analytical and ontological categories in the study of technology and society that has led to the technology acquiring its independent existence and being seen as a distinct thing, or practice interacting at its boundaries with society. This is what is generally referred to as an inter-phase between technology and society. In the process, another disconnect occurs between technical rationality and its experiential meaning — which may be different for managers and users — but that distinction is subsumed by the managerial interpretation based on a rationality that gives technology a unilateral face. This, in fact, is the terrain of struggle, according to Feenberg, for the different actors involved in technology. 'Liberation from technological fetishism will follow the course of liberation from economic fetishism. The same story will be told about machines that we tell today about markets.' He foresees:

> [R]eal change will come not when we turn away from technology but when we recognise the nature of our subordinate position in the technical system that enrols us, and begin to intervene in the design process in the defence of the conditions for a meaningful life and a liveable environment. (Feenberg, 1999)

Not going into the details of this domination or the criticism of technology, we are here trying to understand the other side of the coin. What holds us back from intervening in the design process?

When societies change rapidly, their prevailing ethical norms are challenged both by the basis of new knowledge and the conflicts created by the new practices that threaten prevailing norms. Ethics is the notion of what is just and right in society which guides human action. In other words, it tells us what is right and wrong. This is not a linear process but a trajectory interspersed with conflicts of ideas and interests in various arenas of technology-society interface. The term 'ethics' here includes explicitly normative including societal, political, cultural, and philosophical issues, and the activities and approaches that seek to identify, analyse, and address them as such. In many cases of controversies involving technology and ethics, the policy or ethics evaluation occurs only after the technology has progressed in a significant way, experiments have taken place, and results documented.

The introduction of any new technology comes with ethical and social issues. Nanotechnology is no different. An article titled, 'Mind the Gap: Science and Ethics in Nanotechnology', widely considered as a foundational paper in the field of nanoethics, showed a gap between publications on scientific and ethical aspects of nanotechnology, and concluded: 'As the science leaps ahead, the ethics lag behind. There is danger of derailing nanotechnology if the study of ethical, legal, and social implications (ELSI) does not catch up with the speed of scientific development' (Mnyusiwalla et al., 2003). In a *Nature Nanotechnology* article entitled 'Mind the Gap Revisited', Nordmann and Rip (2009) re-examined the earlier thesis and showed that the gap was closing, but too speculative. According to Khushf (2003), ethics enter the game just as soon as one takes seriously the nanotechnological claim that it will radically transform the organization of knowledge and society. In reports on nanotechnology (National Science Foundation [NSF], 2001; *The Royal Society* and *The Royal Academy of Engineering*, 2004), it appears that research on the ethical and social implications of nanotechnology should be performed to ensure that nanotechnology does not suffer the same destiny as GM food, which faced a public-boycott. It can be inferred that reflections on ethical and societal issues of nanotechnology is indispensable in this context. Furthermore, we question, whether nanotechnology is the same or different than other 'emerging technologies', such as biotech, synthetic biology, cognitive science, etc., whether nanotechnology should be treated as a special case of ethics or whether it poses ethical issues fundamentally similar to other emerging technologies.

Every technology has an inherent bias depending upon the context in which it evolves, yet its impact outside that context depends upon the manner in which it is used: to curtail the potential to create new ethical practices or to question the prevailing practices and values. The question arises here is that—How do social forces shape use of nanotechnology and its progressive potentials, if any? To answer this, we explore the way nanotechnologies are used and their foreseeable social impact.

6.3 Inventory of Socio-ethical Risks in Nanotechnology

Inventing the ethical and social risks pertaining to nanotechnology may be more complex and comprehensive, since it interacts with other technologies, such as biotechnology, information technology, and environmental technology. Disruptive nature of nanotechnology affecting many sectors of the industry may give rise to quite diverse ethical and societal issues compared to other technologies. Mnyusiwalla et al. (2003) identifies the ethical issues in nanotechnology as 'equity, privacy, security, environment, and metaphysical questions concerning human-machine interactions'. Lewenstein (2005) identifies them as environmental issues, political issues, intellectual property issues, and human enhancement. In fact, there exists criticism about whether nano should be treated as a special case of ethics or whether it poses ethical issues fundamentally similar to other emerging technologies (Swierstra and Rip, 2007). This is mainly because nanotechnology only states that the technology deals with the phenomena occurring at a nano-scale, and one cannot find any common ground, such as bio-ethics except the length scale. However, from the characteristics of nanotechnology or nanomaterials, one can draw possible ethical and societal risks which can be considered as nano-specific (Lee and Lee, 2010). Regulatory bodies in the US and the EU have concluded that nanoparticles form the potential for an entirely new risk and that it is necessary to carry out an extensive analysis in this regard. This study proposes a conceptual map where it makes an inventory of potential ethical and societal risks: risk-benefit argument, equity and access to technology, regulation and responsibility, and public participation and engagement.

6.3.1 Risk–benefit Argument

Uncertainties associated with such emerging technologies pose a challenge in risk–benefit evaluation and thus the standard forms of decision-making may be inadequate (Funtowicz and Foladori, 1993). Concerning risk problems, the American bioethicists, Beauchamp and Childress (2001), showed that evaluation of risk in relation to possible benefits can have the features of risk–benefit analysis. To them, risk is anything which causes harm in the future and harm is defined as a setback to interests, particularly in life, health, and welfare. In the field of biomedicine, the term benefit commonly refers to something of positive value, such as life or health. Risk–benefit analysis can be conceived in terms of the ratio between the probability and magnitude of an anticipated benefit and the probability and magnitude of an anticipated harm (Beauchamp and Childress, 2001: 195). The terms risk and benefit, as defined above, are ethically relevant because ethical obligations or principles to inflict no risk and to promote benefit are generally accepted (Beauchamp and Childress, 2001: 4). Nanotechnology has potential benefits and dangers as well in a wide variety of areas; e.g., in health and in the environment, as previously mentioned. Besides, technological risks, the funding risk of nanotechnology is an issue that is not being questioned. Consequently, it drives distinct assumptions about who will benefit and what the benefits will be. Locus of benefit as well as locus of potential harm — individual, family, community, or wider society — also seemed to be operating, although cross-national differences do possibly confound this. High cost is another main factor in this. Issues of trust about the social contract or environmental health and safety issues, of great importance in technological risk perception, seemed to be gendered as well, with different issues, expectations and assumptions voiced by men and women about governments', corporations', and communities' ability and likelihood to manage technologies wisely and for social benefit.

6.3.2 Access, Equity, and Justice

Since nanotechnology-enabled products are expensive, typically reaching better-off groups before disadvantaged ones; poor people are unlikely to be the principal beneficiaries of efforts to accelerate progress towards Millennium Development Goals (MDGs). More plausible is faster progress among privileged groups and a rise in poor–rich technological disparities. In nanotechnology, a technological divide could occur between developed and developing countries. For example, many nano-enabled products including nanomedicines will not be affordable in underdeveloped regions (Hunt, 2007). If at all, should they be allowed to pay its current market price?

The answer to this question is subject to both the gravity of the medical condition of an individual being treated and to avoid the serious side-effects through nanomedication. If access is market-price contingent, then people from developing countries may not have access to such medicines and access only conventional medicines. Will nanotechnology's complex know-how lead to the concentration of decision-making and economic power in the hands of scientific and technocratic elites in developed countries only? Some were suspicious of the multiplier effect that nanotechnologies might have on existing power relations: most developments are spurred by commercial aims, and multinational companies (MNCs) will acquire even more unchecked influence than they already have (Bijker, 2011). Due to their high-tech and capital-intensive resources, the developed countries can invest in this technological innovation. In this context, developing countries may be thwarted by their inability — in both capital and technological expertise — to assess appropriately the possible impact of new technologies. Therefore, those products needed in developing countries will not even be conceived or produced and further lead to the emergence of 'nano-divide' like the current 'IT-divide'. It is possible to question how knowledge and values are given a material existence through technology such that technological artefacts and processes are inherently biased towards the production and reproduction of existing social inequities. Even within countries, justice needs to be served to the extent that each party gets its due share of what is being allocated among members of a group, such as laboratory space, research funds, work time on a high demand research instrument, or credit for a new discovery or theory. For example, in S&T, the highly regarded (and the elite) institutes receive maximum funding as compared to lesser regarded institutes.

6.3.3 Regulation and Responsibility

The problem of effectively anticipating and addressing ethical and social implications of nanotechnology is compounded by the institutionalized practice of regulating nanotechnologies either at the beginning or ending stages of their development cycles, while largely ignoring the development process itself (Fisher, 2007). Early regulation often takes the form of 'yes or no' in terms of funding decisions and priorities, and 'end of the pipe' regulation is often too late to be fully effective. Efforts to assess emerging technology during R&D make sense in terms of cost effectiveness. For instance, 'technology assessment is most effective when applied in the early stages of R&D, when changes are easier' (Tepper, 1996). This type of approach, however, is orthogonal to the 'linear model' of innovation that is used to explain and justify many science policy decisions (Pielke and Byerly, 1998). The linear model is based on the premises that techno-scientific activities are ethically neutral where research funding inevitably lead to development, diffusion, and socio-economic benefits. Looking at the level of knowledge that we have about risks associated with nanotechnology, to what degree should nanotechnology products and applications of this technology be regulated? Do individuals have a *right to know* in order to make informed decisions through labelling mechanism? According to the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST), the Precautionary Principle (PP) applies when there exist considerable scientific uncertainties about causality, magnitude, probability, and nature of harm (COMEST, 2005). The Precautionary Principle (PP) acts as a useful mechanism for guiding the technology where the risks of a new technology are uncertain, unknown, and unpredictable (3Us) (EC, 2008; Health and Safety Executive, 2011). The justification of PP often makes an appeal to responsibility towards future generations. The application of the PP has been adopted by the UN and the EU as a guideline for democratic and science-based governance in such circumstances of uncertain scientific knowledge, but is still contentious and in need of elaboration and translation into policies (Jasanoff, 2000; Harremoes et al., 2002; Stirling, 2002; EC, 2010).

Closely related is the question of choice through responsible nanotechnology development. Though this notion is crucial to policy and research alike, the notion of responsibility is far from being clear and shared, affecting also the coherence of policy formulation and implementation. Unfortunately, Jonas (1984) is not able to say much regarding what should be the content of the ethics of responsibility, or what policies we need to manage in our new world. He despairs that we have too thoroughly destroyed our sense of the sacred to succeed, and maybe because of this he suggests that 'unwisdom' will come up with the best answers. It can be interpreted that the experts' formal training is no longer sufficient to guarantee accuracy. He also points out that action always requires some ethic, consciously chosen or not, and we must exert 'a supreme effort to determine the right one, or else we may be left with a wrong one by default' (Jonas, 1984). Given how dire Jonas sounds, it is likely that he would urge everyone to take up the task of determining ethics that would guide technological policies. He speculates of at least four responsibilities. The overriding responsibility is to try our best, because 'well-intentioned, well-considered, and well-performed' (Jonas, 1984: 118) actions may still put us in grave danger. The English saying of 'if something is worth doing, it is worth doing well' is the common sense understanding of this responsibility. The maxim of ensuring that the 'eventual effects (of our acts are consistent) with the continuance of human agency in times to come' (Jonas, 1984), is its most essential requirement. The other three responsibilities could be raised out of the first. Thus, we should engage ourselves. We should not wait on others to approach us, to draw out our contribution. Instead, we must seek out opportunities to engage ourselves. We should recognize, though, that this is not always easy. If we have never heard of nanotechnology then we cannot be expected to engage in its development. Sometimes, people will need to be engaged by others in order to trigger their own desire to learn more. This is why there is also a responsibility to engage others, in addition to a responsibility to engage ourselves. Another responsibility, that Jonas endorses, is to be aware of the possibilities of our action. This means educating ourselves and others about the possibilities of nanotechnology so as to know which areas of technology are beneficial, and which are risky. It also means that we should not just ban technologies that could harm us, as Joy (2000) suggests. Instead, we should learn about the risks, hazards, and benefits of nanotechnologies and should develop these technologies enough to prepare us for that technology, if it is developed elsewhere. Because no one can know everything about nanotechnologies, our duty to learn implies cooperation, 'and we are more likely to cooperate if we understand how much we have to gain from it' (Drexler, 1986). Cooperation would build cosmopolitan ties of understanding and knowledge sharing, and lead to harmonized regulations for the benefit and safety of all. So, we should encourage a strong, accountable, government-funded presence in nanotechnology. This could provide positive momentum to nanotechnology research while limiting the development of destructive or aggressive applications. Our last responsibility is to avoid harm. As implied, this is now more difficult than ever before since there are so many ways of affecting others unintentionally. With the education we give ourselves we can create appropriate safeguards against nanotechnology-enabled disasters, whether accidental or intentioned. We should be willing to slow development while these systems are put in place. However, we should not block development as nanotechnologies could prevent harm as well as cause it. Rather than live in fear of disaster, we can instead create and hope that humanity works quickly enough to avoid the worst of the dangers. We should certainly be cautious but we should not abandon the possibility that with some foresight, we could improve the lives of billions.

6.3.4 Public Participation/Engagement

With the increase in nanotechnology-related commercial products available in the marketplace, the public[1] is still largely unfamiliar with the potential risks and benefits of this emerging technology. An opinion piece was published in *Nature Materials*:

> For emerging areas of science and technology, public acceptance is a vital precursor to sustaining their development. Scientists and industrialists working with GM foods have learned this the hard way. There are now signs on both sides of the Atlantic that funders of nanotechnology research are starting to take the issue of public acceptance seriously and learn from others' mistakes. (Nature Materials, 2003)

Forget about the developing countries, studies in developed countries like the US show that majority of the public are unaware of the emerging technology (Scheufele and Lewenstein, 2005). The proper knowledge of the public on any possible risks of the products of a new technology is very important to overcome public reluctance to its adoption, as can be seen in the cases of GM crops and nuclear plants. Therefore, applied scientists and technology researchers should provide proper information with scientific test results on the products of a new technology, especially those related to the ethical and social problems, if they want to develop them. Any emerging technology needs public consensus and/or some legitimate supports from the public for its progress. Unless the government and industry were to work on building public confidence in nanotechnology, the public may reach to boycott the

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[1] The 'public' is not a homogenous group rather a vast and heterogeneous group of the 'publics', who are concerned by a specific problem or issue. Each public has its own unique expectations, interests, hopes, and fears about science in general and nanotechnology in particular

nano-enabled products in future, resulting in huge socio-economic losses. Early engagement of developing countries in nanotechnologies is important in order to avoid that this new technology deepens the 'global divide' rather than helps bridging it. While developed countries are encouraging different ways of public participation (e.g., consensus conferences, citizen juries, deliberative technology assessments, science shops, deliberative polling, and other techniques) to assess the impact of nanotechnology development, this is rare in developing countries.

For the responsible development of any emerging technology, a diverse stakeholder engagement has been emphasized upon (NSF, 2001; Hunt, 2007; Roco and Bainbridge, 2001; Lewenstein, 2005; Singer et al., 2005; Choi, 2007; Stebbing, 2009; Patra et al., 2010). Public participation is required not only because the risks of a new technology cause concern but also due to the controversies that arise when people are unable to ask more fundamental questions: Who will take responsibility if, when things go wrong and can we 'trust' scientists? Trust refers to citizens' willingness to rely on the endorsements of experts, such as scientists and regulators, as well as institutions, such as the government, to manage risks associated with emerging technologies (Luhmann, 1979; Giddens, 1991; Earle and Cvetkovich, 1995; Sztompka, 1999). Giddens (1991) pointed out that trust in a variety of abstract systems is a necessary part of everyday life, and the characteristics of abstract systems imply constant interaction with 'absent others' — people we have never met but whose actions directly affect our lives. Irwin and Wynne (1996) demonstrated that people were much more concerned with whom to trust than with the scientific aspects of an issue itself. According to risk communication scholars, trust acts as an uncertainty reduction mechanism over the unforeseen risks and costs of emerging science and technologies (Freudenberg, 1993, 1992; Slovic, 1999). Trust as a tool in decision making is efficient when individuals have limited knowledge and personal experience, and when they have little chance to anticipate the future consequences of a particular technology (Olofsson et al., 2006). This is highly applicable to the emerging nanotechnology field with which most people are unfamiliar.

6.4 Socio-ethical Works

6.4.1 International Developments

Several developments over the past five years, has brought the concerns regarding socio-ethical works of nanotechnology. In 2000, Bill Joy, the then Chief Scientist of Sun Microsystems, published an imaginary essay in which he termed the potential of nano-scale assemblers for destructive self-replication a threat to the biosphere. In 2003, Michael Crichton's best-selling novel *Prey* depicted unpredictable swarms of programmed and learning-capable nanoparticles wreaking havoc on humans. Since 2003, when the NSF published a request for proposals to establish a National Nanotechnology Infrastructure Network (NNIN), NSF has required that nanotechnology's 'social and ethical implications' be a part of NNIN's research agenda. The NSF has established two 'Centers for Nanotechnology in Society' in US universities to study societal and ethical issues related to nanotechnology. In 2007, *Nanoethics*, a new scholarly journal about nanotechnology and ethics, was launched. The journal and its title indicate that some academics believe there are societal and ethical issues associated with nanotechnology that demands critical analysis.

In recent times, global and transnational development of nanotechnology has been increasingly studied along with socio-ethical studies. Socio-ethical studies of nanotechnology outside of the West (the US, the UK, Denmark, and Germany) have somehow remained marginal in such analyses despite the fact that so much of nanotechnology R&D and collaboration is going on in Asian region in general, and particularly India.

6.4.2 Developments in India: Contextualizing Socio-ethical Risks

As mentioned in previous chapters, DST launched the Nano Science and Technology Initiative (NSTI) in 2001 with an allocation of $15 million over five years. This was followed by a Nano Science and Technology Mission (NSTM) in 2007 with a funding of Rs 1,000 crore (approx. $254 million) for five years. Nanotechnology research in India is organized in four sets of institutions. Much research is conducted in the national laboratories and in various institutes of the ministries of the central government. Research is also undertaken by the universities, institutes of technology, and certain autonomous research institutes and finally, there are industrial research programmes in private business enterprises. But, the industrial research programmes do not have active connections among these various types of institutions. Semi-structured interviews were conducted across 15 scientific organizations across the country, including universities, public R&D institutes, institutes of technology, and institutes of science.[2] To locate nanotechnology researchers for interview, we used a purposive sample of organizational representatives, followed by a snowball sample. We limited ourselves to the most advanced centres of teaching and research in nanotechnology fields which set the trend in India. We ensured the representative of scientists from different disciplines, such as materials sciences and engineering, chemistry, physics, biological sciences and social sciences, electrical engineering, mechanical engineering, instrumentation science, and toxicology for this inquiry. Qualitative data in the form of participant observations, interviews, and document collection was used to study the perceptions of scientists on different socio-ethical risks. Participant observations of nanotechnology research activities at these organizations, and meeting between experts, and other government representatives offered a basis for interpreting interview data. A variety of written materials from government and non-government sources were also collected for the purpose of reconstructing past events, including the development of nanotechnology research in India. Interviews were face-to-face and open, guided by pre-designed and tested questionnaires, which were audio-recorded and then transcribed. It was noted that scientists/researchers located within an organization had varied views regarding the various socio-ethical issues associated with nanotechnology. Therefore, organizational/disciplinary affiliations do not play any significant role in shaping the perceptions of scientists.

6.4.2.1 Perception on Scope for Funding and Resources Among the Scientists

One of the important societal risks associated with S&T field is funding. Sometimes funding makes scientists to shift to a particular S&T field which is nicely funded. The same thing happened to nanotechnology, and huge funding described the shift to working in this field as a 'logical migration', besides cutting-edge areas of S&T. When one looks at the funding issues of nanotechnology in India, it is seen that bigger (and elite) institutes were reported to receive maximum funding as compared to smaller institutes/

[2] The field visits were carried out during December 2009 to February 2010 in 15 scientific institutions/organizations/laboratories of India. The total number of scientists interviewed were 35.

universities for research in nanotechnology. These are the Indian Institutes of Technology (IITs); the Indian Institute of Science (IISc) and Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR) in Bangalore; the Tata Institute of Fundamental Research (TIFR) and the Bhabha Atomic Research Centre (BARC); International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) in Hyderabad; the Indian Association for the Cultivation of Sciences in Kolkata. This produced an unequal distribution in funding due to improper allocation of funds.

Even the massive infusion of research funds showed that too many institutes were involved in nanotechnology research without having capabilities. A chemist located at University of Delhi, also known as a 'man of patents in nanotechnology' in India saw negatives in nanotechnology research in India, suggesting that 'me too' research in nanotechnology implies:

> I am doing it; why don't you. If…then you receive funding.

The smaller institutes and universities, by and large, have been supplied with relatively small resources for research in nanotechnology. As a result, he explained some common experiences of Indian scientists where their ongoing research was, all of a sudden, re-termed 'nanotechnology'.

Nanotechnology is perceived by the scientists as an interdisciplinary field which requires knowledge from biology, chemistry, materials science and metallurgy, physics, and the engineering sciences. The interdisciplinary nature of nanotechnology demanded the trained labour force for R&D. But, the lack of qualified human resources for working on it according to prevailing standards of accuracy can cripple the scientist. In addition, scientists advocated for specific training programmes for PhD and post-doctoral positions. Adequate training is required even at the operational level for the technicians. However, the need for additional incentive, such as training grants was emphasized upon by the scientists and engineers.

6.4.2.2 Perceived Risk vs Benefit of Nanotechnology Among the Scientists

It was observed that almost Indian scientists confirm to the presence of risk in any emerging technology, implying nanotechnology is not risk-free. A varied risk perception existed among the scientists subject to the nanotechnology application-specificity. For instance, applications within the health area were considered more negatively among scientists than applications in the field of electronics.

Scientists' views were clubbed into two categories such as 'supporters' and 'risk-tolerant supporters'. Both the categories were similar in being supportive, but they displayed different perceptions of risk in nanotechnology. For the 'supporters', risk was not an issue. The 'risk-tolerant supporter' perceived risks but then discounted it and never asked for it to stop nanotechnology development. Scientists were asked whether they take any precautions while dealing with nanotechnology research or enabled products. It was reported:

> There were no 'special' precautions taken by the scientists during their laboratory work on nanomaterials. There was a 'laid-back' attitude towards safety; moreover, talk of safety was considered among scientists as mere rhetoric; unsafe actions and practices are handled ad hoc and typically 'winked at' or penalized with a 'slap on the wrist', and individual researchers do not care about how other researchers conduct themselves as long as they are left alone to work as they want to.

However, they indicated that safety protocols for R&D in nanotechnology in general need to be developed. Some scientists recommended that 2–5 per cent of their research budgets to be spent for the implementation of precautions and best scientific practices in laboratories. Scientists asserted that such kind of mechanisms needs to be fed into R&D and policy. On being asked whether scientists consider studying risk issues, almost all scientists were reported negative. Though scientists were concerned about risk issues but they might not be able to afford time to risk issues. It emerged that scientists want policy-makers to take the initiative to develop the environment for assessing risks while technology is evolving.

In India, the issues of risk and toxicity were also addressed by toxicologists which later got supplemented by social and legal scientists. It was found that there was no complete understanding of the toxicity of nanomaterials among the scientists. Since there is no complete understanding, it would be difficult to map all the risks.

6.4.2.3 Perception of Regulation and Responsibility Among the Scientists

Even on the approach to regulation, there are differing views, whether to adapt existing systems for nanotechnology products, or to have a separate regulatory system. The scientists' responses were recorded at three levels, viz., at the beginning of research, at any stage of research, and at the production level.

At the beginning of nanotechnology research, scientists want absolute/complete freedom. But, the argument hardly applies to nanotechnology, however, because first, its products are not only ideas but also new substances changing the material world and second, lack of knowledge about these materials might outweigh the risk of unintended harm over benefits.

At any stage of nanotechnology research, a group of scientists advocated for regulatory measures with safety guidelines. Their argument is that, 'no research is completely free from some kind of monitoring…', and for them, safety guidelines will be acted as a mechanism for valid standards of controlling and ethically justified.

At the large-scale nanotechnology production level vis-à-vis specific applications, one group of scientists argued for the involvement of various stakeholders in order to avoid some ill-effect on the environment and society. Another group of scientists recommended for sector-specific regulation in nanotechnology. For example, in the field of health, nanotechnology can be beneficial for prevention, diagnosis, and treatment of illnesses and disabilities. In fact, the development of nanotechnology enables early diagnosis and better treatment with transplants and cellular repair systems. Some avenues of research in nanotechnology include the incorporation of machines in human systems. When it comes to the question of implanting artificial materials or machines in human system, scientists think the question of ethics take a front-seat. In this case, some scientists were proponents and some were opponents. However, in the case of toxic materials, all scientists agreed that 'we don't want it'.

It was learnt that there is an absence of the regulation of nanomaterials and nanotechnology in India. In this regard, as discussed above, regulatory efforts were proposed, but scientists admitted their lack of knowledge about the long-term safety of nanomaterials. Furthermore, they don't know everything. Scientists agreed that the duty to contribute to a responsible nanotechnology development as part of their ethos, but they more or less explicitly rejected taking 'responsibility' for any consequences of the knowledge they produce beyond quite narrowly defined imminent risks arising from their work. They argued that taking any role in development of these consequences is not part of their professional role because they create or generate the knowledge from their research, but others decide how the knowledge is to be used.

Whether this separation of responsibilities is ultimately sustainable is another matter, but for the moment we shall accept it. However, scientists suggested that a mechanism could be considered for providing a platform for discussing the complex meanings of responsibility in nanotechnology R&D and license to industries/laboratories dealing with manufacture or usage of nanomaterials.

6.4.2.4 Perception of Education and Public Dialogue Issues Among the Scientists

A noteworthy ethical issue sometimes involved in public funding is hype,[3] deliberately exaggerated claims intended to serve the exaggerator's interests. In research, hype can exist at two levels. At the level of a particular research field as a whole, hype would occur if in testimony before a key government funding agency. Nanotechnology researchers touted the nanotechnology field with 'the next manufacturing Revolution', 'developed technology', 'enabling technology', 'fantastic technology' and asserted that it will 'transform the human lives'. At the level of an individual research proposal, hype would occur if, in order to gain funding, a nanotechnology researcher exaggerated a project's feasibility, likely results, or significance. While hype may seem essential to researchers given the highly competitive nature of the research funding game, it is ethically irresponsible. Hyping is ethically irresponsible for two reasons. Good science could go unfunded if a hyped field or project is funded or over-funded, and hype in the form of exaggerated claims about research payoffs to the public could erode public willingness to continue or increase funding for science and engineering. Hyping one's application for funding might seem ethically worse than hyping one's field of specialization in hopes of gaining increased funding for it. However, both

[3] Instead of 'hype', lawyers often use the expression 'non-actionable puffery'.

sorts of exaggeration are wrong. If successful in serving the hyping party's interests, each carries significant opportunity costs: potentially fruitful research on other projects or in another field may go unfunded because a hyped project is funded or a hyped field is over-funded. That outcome may effectively sustain harms that would have been diminished or overcome had the unfunded research been funded and succeeded. Just because hyping one's research field only indirectly benefits the hyper, it does not make such hype ethically permissible. Media's potential of creating the hype that nanotechnology will solve all the problems emerged as an issue of concern.

The need for greater public awareness of nanotechnology was felt by the scientists. Awareness in nanotechnology through public lectures, awareness programmes on nanotechnology; for example, Nano for Kids; Nano for Xth and XIIth standard students; demonstrations, and activity-based kits were suggested. Also, it was suggested that the nanocommunity should come forward and publicize more materials in this regard and the government should advertise on-going nanotechnology research in India. A viewpoint also emerged about the awareness generation under the larger science popularization programmes.

6.5 Concluding Remarks

New technology is often seen as a threat to existing S&T structures and their associated value systems. In addition, groups opposing nanotechnology are drawing on environmental and human health concerns when challenging regulatory and marketing decisions. The issue, therefore, is not simply one of providing more information to reduce uncertainty, but rather one that requires a deeper understanding of the structural benefits and risks posed by the use of nanotechnology. The debate about nanotechnology must be couched in a broad context. As can be seen from the survey, we do not have yet enough information about the risk of nanomaterials to build a database for such matters. Moreover, the research on socio-ethical risks is time-consuming, capital and cost-intensive to get meaningful results. The need of ethical considerations in nanotechnology researches, especially in the fields related to health, can be easily inferred. Nanotechnology will influence broadly our life and society revolutionizing many sectors of production industries. The problem is that nanotechnology has a potential to bring some unexpected side effects wrecking human health and environments. And its visibility indicates that it has entered the steady stage of technological innovation where social agreement is crucial for its broad diffusion to the public as IT does currently. One of the problems in forming social consensus at this stage is that people are easy to be fallen into their own traps of being unconditionally enthusiastic or being exaggeratedly loathsome about an issue. Therefore, to avoid this trap, we need to argue about the positive and negative effects of nanotechnology with an equal balance. The major challenges for governance of nanotechnology is to strike the appropriate balance between benefits and risks/uncertainties; between promotion and regulation of innovation; between what is feasible technically and commercially, and what is publicly acceptable and desirable; and to deliver the claimed societal benefits without challenging accepted societal norms (Lyall and Tait, 2005).

As today's scientists and engineers probe new areas of inquiry that promise major social benefits but are also socially controversial, society needs and is beginning to demand researchers hybrid competence: state-of-the-art technical knowledge coupled with a sensitive ethical compass. To paraphrase Samuel Johnson (1759), 'while (ethical) integrity without (technical) knowledge is weak and useless, (technical) knowledge without (ethical) integrity is dangerous and dreadful'.

Scientific literacy is often regarded as a contributor to sustainable development (Holbrook, 2009), since a more scientifically and technologically literate population is more likely to make environmentally and ethically wiser and more responsible decisions. Nanotechnology education must be part of the response to the 'grand challenges for citizens and societies', such as climate change or health care.

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CHAPTER 7

Regulating the Risks of Nanotechnology: Issues for India

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7.1 Introduction

The term 'regulation' essentially relates to government action in the form of laws and notifications with the objective of directing private action for a specific purpose or with certain aim (Brownsword, 2008). As a legal instrument, it is also referred to as delegated legislation or subsidiary legislation that is prepared under the aegis of a legislative instrument for the fulfilment of the objectives, which this particular instrument seeks to serve. It can be variable in nature, ranging from penalty for prohibited acts to that of providing a system of incentives for preferring one kind of action over another. Regulation, therefore, refers to a gamut of both soft (incentive-based) and hard options (prohibitions) that directs parties to choose certain course of actions over others (Black, 2001). It could be permissive in nature (giving guidelines about what practices and areas of research will be permitted and what kind of frameworks will govern the fruits of the endeavour) or prophylactic (against potential dangers and risks) or a combination of both.

Despite the various forms which regulation can take and the different objectives it is supposed to serve, regulation in the modern world is generally perceived as a means by which risks can be controlled. This is more so when we talk about regulating a technology; the purpose of such regulation generally being to manage the risks, both known and unknown associated with it. This pre-occupation with 'risk-based regulation' in modern states, particularly Welfare States, stems from the fact that the state owes both a direct and indirect responsibility towards its citizens to protect them against risks. According to Giddens (1999), the Welfare State is essentially a risk management system, designed to protect against hazards that were once treated as the domain of the gods — sickness, disablement, job loss, and old age. While risk has always being a part of humankind's experience, in the modern age, risk assumes a new character altogether; the main distinguishing feature being that modern risks are more the product of human activity — 'manufactured risk' — than those produced by non-human factors or 'external' risks (Giddens, 1999). Beck (2006), who coined the term 'risk society', says that modern society is increasingly turning into a risk society in the sense that it is increasingly occupied with debating, preventing, and managing risks that it itself has produced.

In the modern risk society, the government or the state is fast emerging as the 'ultimate risk manager' (Moss, 2002, in the context of the US) and the success or failure of a society in responding to risks becomes a measure of the capacity and responsiveness of its government (Quiggin, 2007). This was not always so; the proper role of the government in managing risks for its citizens has been subject to much debate over the years in most developed countries, such as the USA and the UK; this debate is, however, outside the scope of this chapter.

In recent decades, risk has become 'a new lens through which to view the world', with governments in advanced industrial societies increasingly engaging in a risk-based approach. According to Hutter (2005), during the 1980s and 1990s, regulatory discussions in a number of such countries incorporated an imperative to adopt risk-based strategies and tools, in some cases heightened by the state's co-option of corporate risk management systems. This gave rise to risk-based regulation which in the words of Rothstein et al. (2006) can be described at its simplest as 'allocating resources in proportion to risks to society (such as health, safety or environmental risks) considering both the impacts themselves and the likelihood that they happen, in order to establish appropriate levels of control'. In Hutter's view (2005), the elements of such risk-based approach to regulation are various.

At a minimum, they entail the use of technical risk-based tools, emerging out of economics (cost–benefit approaches) and science (risk assessment techniques). There is another integrated and more holistic approach to risk management which conceptualize risks as interrelated to each other and as having potential consequences for broader economic, natural, social, and political environments. Traditional risk management of hazardous agents is generally based on one of the following three models: (*i*) acceptable risk, (*ii*) cost-benefit analysis, and (*iii*) feasibility or best available technology (Marchant, Sylvester, and Abbott, cited in Schummer and Pariotti, 2008). The acceptable risk approach depends on risk assessment to describe the risks of an agent, which it then seeks to reduce to socially acceptable levels. The cost-benefit model tries to consider both the costs and benefits of proposed applications, while the third model requires reduction of risks to the lowest level technologically or economically feasible, without requiring information about risks or benefits.

7.2 Imperative for Risk-based Regulation of Nanotechnology

The focus of risk societies being on 'manufactured risks', governments all over the world — particularly in the developed world — are slowly but surely realizing the need to regulate the risks arising from emerging technologies, while promoting their development. Fiedler and Reynolds (1994) and Hudson (2003) point out that in the specific case of emerging technologies like biotechnology and nanotechnology, given the potentially adverse health and environmental impacts of these technologies, the most widely publicized policy discussions have been on the question of risk regulation. Nanotechnology is expected to challenge the existing regulatory structure, in terms of its ability to adapt itself to this new technology. The current scientific uncertainty about the health, safety, and environmental risks of nanotechnology could act as a big deterrent to the application of traditional risk management approaches to its regulation. Traditionally, the process of risk assessment for the purpose of regulation is usually informed by factual evidence, usually obtained from toxicological, environmental or epidemiological studies, which is only gradually developing in nanotechnology. In the absence of full scientific certainty about the risks, as is the case with nanotechnology, the precautionary approach is often resorted to. According to the Report of *The Royal Society* (2004), an assumption then has to be made about the potential hazard on the basis of such evidence as is available (e.g., by analogy with materials of known toxicity) and the best available judgements about hazard-inducing properties of the substance. It must be accompanied by an assessment of the risk of exposure, for example in the workplace or to the general public from the use of such products.

The precautionary approach has been very hotly debated with critics arguing that because of its ambiguity, it is prone to arbitrary decision making, is biased towards the status quo, is an inflexible regulatory tool, and its application does not allow it to consider properly the advantages of new technologies. Nevertheless, the principle serves to promote a dialogue on what to do if risks have to be anticipated on uncertain scientific bases and in this sense, would contain a proactive and pre-emptive approach to uncertain risks rather than a proper rule for decisions (Schummer and Pariotti, 2008). The precautionary approach has been accepted to have two forms — a strict and active form (D'Silva, 2007). The active form calls for choosing less risky alternatives when they are available and for taking responsibility for the potential risks. On the other hand, the strict form requires inaction when faced with a risk. There is some consensus that following the strict form for nanotechnology would result in all research and development (R&D) coming to a standstill; thereby, the active form is more suitable to take care of risks from such an emerging technology, while not hindering its development.

Concerns have been expressed in several quarters regarding the potential impact of nanotechnology, which have ranged from the fantastic 'apocalyptic threats' (Joy, 2000; Hughes, 2007) to the genuine. While 'apocalyptic' threats may seem unreal, there are many genuine health and safety concerns in relation to human exposure to nanomaterials which is vindicated by increasing scientific research. However, it needs to be stressed that there is presently considerable information deficit with regard to the properties of nanoparticles and, in particular, on how their very small size might influence toxicity. Adequate research is yet to be done on their potential impact, if they enter the human body or are dispersed into the environment.

Despite this, many nano-based products are already in the markets, both in developed and developing countries, in the absence of any kind of regulation. This also seems to be the state in India, with the Indian government preoccupied with development and application of nanotechnology rather than on its risk assessment and regulation. To some extent, the preoccupation of the Indian government stems from the fear of being left behind in the nanotechnology race. The scientific establishment in India echoes this sentiment: 'We missed the opportunity during the semi-conductor revolution. We should not repeat that with nanotechnology' (Srivastava and Choudhury, 2008).

In the context of how best to address the risks from nanotechnology, different views have been expressed. According to Joy (2000), the best way to prevent technological apocalypse will be to 'relinquish' emerging bio, info, and nanotechnologies. On the other hand, the watchdog group, ETC (2003), advocates a moratorium on commercial production of new nanomaterials and launching a transparent global process for evaluating the socio-economic, health, and environmental implications of the technology. Critics point out that technology moratoria or relinquishing technologies cannot be a practical proposal to address the risks, since they cannot and will not be implemented (Hughes, 2007). In a conference on regulation of nanotechnology at the Foresight Institute in 1999 (which led to the development of the Foresight Guidelines), participants agreed that nanotechnology would be developed regardless of any effort to suppress it, and that such efforts would only ensure that whatever research took place would do so in rogue nations, with few constraints (Reynolds, 2001). There is some consensus worldwide that appropriate controls in the form of regulation, must be tailored to address the evolving problems and potential risks of nanotechnology, promote its benefits and attenuate its social and economic upheavals (D'Silva, 2007).

In this chapter, the broad objective will be to examine the existing regulatory framework in India, in terms of its capability to address the risks of nanotechnology — if they materialize and map the regulatory landscape in India — which could hold relevance for nanotechnology.

7.3 Problematics in Developing Risk-based Regulation for Nanotechnology

Nanomaterials could be covered by the general scope of many of the existing legislative frameworks on chemicals, drugs and cosmetics, insecticides, food safety and standards legislation, occupational health and safety, environmental legislation, waste disposal, etc. However, what has worried observers is the fact that it is often unclear if current regulation is actually applicable when it comes to specific nanomaterials and their diverse applications (Hansen, 2009: v). The main problems in this respect are:

- Requirements to do safety evaluations are triggered by production volumes by tonnages not tailored to the nano-scale
- Unavailability of metrology tools
- Profound lack of (eco)toxicological data
- No risk thresholds and occupational exposure limits can be established with existing methodologies.
  (Hansen, 2009; Franco et al., 2007).

There are a number of difficulties associated with framing a risk-based regulation for nanotechnology. The primary challenge comes from the fact that traditional risk management approaches have not been designed to anticipate a new technology like nanotechnology and it is very difficult to regulate and manage its risks, using existing approaches, such as acceptable risk, cost-benefit or feasibility.

The difficulty in adapting any one of the existing models of risk-management for regulating the risks arising out of nanotechnology spring from the very basis of nanotechnology which makes it so attractive — the design, manufacture, and manipulation of materials at the nano-scale which due to their tiny size possess unusual or novel physico-chemical properties in comparison to their larger analogues. It is due to these unusual properties that nanomaterials might pose a hazard when in this form, while they do not do so in bulk forms. At the nano-scale, nanoparticles might possess a higher ratio of surface area in comparison to volume and so display greater chemical reactivity. This, together with the physical dimension of the particle itself, shapes chemical composition, surface charge, and agglomeration state and solubility, might influence the nature of its toxicity (Goswami et al., 2008). To cite an example, gold is inert in its natural bulk form but it becomes very reactive at a particle size of 2–5 nm. While the chemical compositions of the two are identical, their very different chemical properties are the result of the different physical sizes. However, in existing regulations, nano-scale versions of existing substances are treated in the same way as the equivalent bulk material, even if they have very different properties. Then again, toxicity of nanomaterials appear to be determined not only by size but by a complex set of characteristics, including size, surface area, chemical composition, coating, shape, route of exposure, etc. The implication upon regulation is that thresholds will have to take into account not only size but factors, such as surface area, coating, shape, etc.

Another formidable challenge in assessing the risk management of nanotechnology is its 'converging technology' nature. According to Calster (2008), the management of the risks posed by the various scientific disciplines require these various disciplines to 'speak' to one another as to the potential hazards of the application. This is difficult as with increasing technological advance and specialization, individual scientists can hardly foresee the consequences of their discoveries for related fields. Moreover, England's Royal Commission on Environmental Pollution in a 2008 report came to the conclusion that nanomaterials are hugely variable in their nature. They are not a uniform class of materials, and hence, attempts to regulate or legislate solely on the basis of their size (1–100 nm in one or more dimensions) or how they are made would be misguided. According to Hoet et al. *(*2004), since a universal nanoparticle to fit all cases does not exist, each must be considered individually in the context of Environment, Health, and Safety (EHS) risks. A 'case-by-case' approach could be expected to impose a very heavy burden on the regulatory structure, more so in developing countries.

Problems with assessing the risks of nanomaterials are compounded by the fact that current risk assessment guidelines based on conventional methodologies are inadequate and metrology tools might be unavailable to measure nano risks.

Again, most importantly, hindrances to nanotechnology regulation come from the fact that there is great uncertainty on the nature and extent of the hazards nanotechnology could pose. In the face of uncertainty, meaningful risk assessment involving hazard identification, dose-response assessment, exposure assessment and risk characterization cannot take place for nanotechnology, which is the first step of any effort towards regulation. Then again, there is the question as to how the technology is to be regulated, in terms of its different products/applications or in terms of the phases of its application, at the stages of laboratory, factory floor, shop, consumer, etc.

The problems in developing risk-based regulation are particularly compounded for a developing country like India, which might lack the resources as well as the capacity to engage in risk research, which is a given for risk-based regulation. Implementation of a risk-based approach even if it materializes may be quite difficult in India, if we go by past experiences in other technologies like Genetic Modification (GM) technology which highlights India's miserable track record in monitoring and enforcement capabilities. In the case of Genetically Modified Organisms (GMOs), though

India has modelled its biosafety regulations on the line followed by leading OECD countries and have established a three-tiered regulatory structure, there are serious shortcomings in the implementation, owing to a number of factors like lack of appropriate mobilization of existing capacity, lack of transparency and public involvement, etc., (Indira et al., 2005). Also, in the event of some of the risks materializing, the capability of developing countries to handle and mitigate them is quite suspect, based on past experiences, Occupational and Health Safety (OHS) rules and precautions are underemphasized, poorly monitored, and enforced.

7.4 Taking the First Steps to Nanotechnology Regulation: The 'Incremental' Approach

Despite the uncertainties, a beginning has to be made in adapting legislation frameworks and risk management approaches to deal with the risks of nanotechnology. According to Hansen (2009), a good starting point could be to understand the limitations or gaps of the current regulation in regard to nanomaterials and thus, initiate the process towards adapting existing laws and facilitating discussion about what kinds of regulatory options is best to address these.

There are many reasons offered against the need for creation of a special regulatory regime for nanomaterials. On the grounds of regulatory economy, the first responsibility of regulators is to always review the robustness of the current operational frameworks to see whether they will be able to address the challenges posed by the new developments and/or to identify key amendments, which would be required to bring the framework into line with current developments (Reynolds, 2003). In the particular context of a developing country like India, a new regulatory framework is not advisable considering the vast scale of public resource investment that is required in the framing and implementation of a new framework. The first task of the regulator should always be to ask the question that whether the current regulatory framework can be adapted to deal with the new regulatory challenges that emerging technologies throw up.

According to the report of the Royal Commission on Environmental Pollution (2008), not only is the legislative field already crowded, but nanomaterials do not constitute a unified class of substances. It further states that it does not matter that nanomaterials are created by a particular technology or that they are of a particular size. What matters is what they do, and the implications of their properties and functionalities for environmental protection and human health. It concludes that there is no logical reason why size of particle should in itself provide the basis for new regulatory controls. The European Commission, Health and Consumer Protection Directorate General (2004) has also arrived at an understanding that the possibility of a specific regulation on nanomaterials is currently unfeasible and it has adopted an 'incremental approach' which adapts existing sectoral laws to the regulation of nanotechnologies in Europe. This approach is defined as the launch of a process which uses existing legislative structures (e.g., dangerous substances legislation, classification and labelling, cosmetic legislation, etc.) to the maximum, revisits them, and when appropriate only, amends them in order to deal with nanomaterials. This approach also includes issuing recommendations, commissioning studies, promoting risk assessment throughout the life cycle of a nanotechnology, encouraging actions of existing institutions, supporting observations of nanotechnologies, initiating a minimalist, appropriate and proportionate regulatory intervention, and setting up of a framework within which stakeholders can help shape the course of nanotechnologies.

Frater et al. (2006), in an overview of existing EU/UK regulation, has expressed the view that current regulation was never designed with nanotechnology in mind. As a result, it is inevitably piecemeal and contained in various statutory provisions spread over different areas of regulatory activity. Nonetheless, they suggest that the existing framework can be adapted generally by ensuring that where appropriate, the regulation extends to nanomaterials. Similarly, in the context of the US, Davies of the Woodrow Wilson International Centre for Scholars (2008) has suggested that the regulation of nanotechnology could start with amendment of existing laws, such as the Toxic Substances Control Act, which oversees all chemical substances in the US and that nanomaterials should be defined as 'new' chemical substances under it to trigger regulatory oversight. He has also recommended changes in the Federal Food, Drug and Cosmetic Act, Federal Pesticide Law, the Consumer Product Safety Act, and existing regulations on Occupational Safety and Health.

7.5 Applying the 'Incremental' Approach to Nanotechnology Regulation in India

In India, although there does not exist a nanotechnology-specific regulation currently, there exists a whole range of regulatory instruments across sectors that do and will extend to the nanotechnology applications in India. However, given that these instruments have been designed for regulation of different aspects of technology development and commercialization in general, their adequacy and capacity to address the concerns emanating from nanotechnology development is indeed something that needs an in-depth critical analysis and deliberation.

We have developed a regulatory matrix comprising several central Acts, rules, and notifications which could have relevance for regulation of environmental risks, occupational health, and safety risks arising from nanotechnology development and applications in India and have categorized them under the following broad heads:

- Production and Marketing
- Occupational Health and Safety
- Environmental Health
- Waste Disposal

An attempt has been made to gauge regulatory flexibility of a few of the instruments under these sectors in terms of their ambit and substantive rights/obligations/responsibilities to respond to nanotechnology developments and risks emanating therefrom.

7.5.1 Production and Marketing

Here, we have analysed in detail three separate legislation for very different products and sectors: first, for drugs and cosmetics, since most of the product development in India is taking place in this sector; second, for insecticides and pesticides, because use of nanotechnology for agriculture is being spoken about as a priority area and of late some developments in the field of nanopesticides also has taken place in India; and third, for food safety, since nanoapplication in food items may have serious ramifications and our food safety legislation is fairly new.

7.5.1.1 The Drugs and Cosmetics Act, 1940

The Drugs and Cosmetics Act of 1940 regulates all aspects of drugs and cosmetics pertaining to their import, manufacture, distribution, and sale in India. Any manufacture or sale of drugs has to be in compliance with the

[1] Section 16

standards laid down in the schedule of the Act.[1] A patent or proprietary medicine cannot be sold, unless the true formula or list of active ingredients contained in it along with the quantities thereof is displayed in the prescribed manner on the label or container.[2] While the inspector is empowered to collect sample, inspect, and seize drugs,[3] the central government is empowered even to prohibit manufacture, etc., of drug and cosmetic in public interest.[4] Such a prohibition can be imposed on import of drugs as well where such import is likely to involve any risk to human beings or animals or does not have therapeutic value.[5]

One of the most important provisions of the Act relevant to growing nano-based health applications in India is the very definition of 'drugs' under the Act. The definition of 'drug' includes medical devices.[6] These will thus include gold/silver nanoparticles for targeted drug delivery, stents, implants, nanoceramics, etc. Although the Act mandates labelling of the list of active ingredients, not much progress can be made in terms of bridging the information gaps around the use of nanoparticles, unless there is consideration of nanoparticles as either new or modified ingredients. Currently, for patented and proprietary medicine, the prescribed labelling standard format puts no obligation to disclose the use of nanoparticles as ingredients.

7.5.1.2 Insecticides Act, 1968

The Insecticides Act was legislated to regulate the import, manufacture, sale, transport, distribution, and use of insecticides with a view to prevent risk to human beings or animals. The Act lays down a framework for registration of any new manufacture, import or sale of insecticides/pesticides and obtaining license thereof.[7] A registration Committee is constituted to register insecticides after scrutinizing their formulae and verifying claims made by the importer or the manufacturer, as the case may be, as regards their efficacy and safety to human beings and animals.[8] While making any application for

[2] Section 18
[3] Section 22
[4] Section 26A
[5] Section 10(A)
[6] Section 3(b) iv
[7] Section 9 and 13 (1)
[8] Section 5(1)

such use, toxicity of the products to human beings, wild life, aquatic animals has to be disclosed.[9] This creates difficulties for nanopesticides in the absence of sufficient information about their toxicity.

However, the Registration Committee can also recommend for a provisional registration up to two years, where the insecticide is being introduced for the first time. In nanopesticides, where all the risks are yet to be defined, a provisional registration would be useful as a short- to medium-term regulatory measure, which ensures promotion of technology while reserving the right to take it off the shelves at a later date, when there are more certainties about the advantages (or lack of it).

The state government may require a mandatory reporting of all occurrences of poisoning (through the use of handling of any insecticide). Reporting requirement should be mandatory across states and not left for states to notify. Moreover, it should not be restricted to poisoning but any adverse reaction/effect. Reporting is an important post-marketing tool and in case of merging technologies, when risks may emerge at a later date, such reporting would be helpful.

7.5.1.3 The Food Safety and Standards Act, 2006

Nano application in food items may have serious ramifications as nanoparticles could be ingested as food ingredients or additives. It has been indicated that inclusion of nanomaterials in food packaging might be significantly risk-free unless residue seepage into foodstuffs cause them to be ingested. Similarly, soluble nano-sized additives and nutrients might also not pose risks significant to the kind these additives already do. On the other hand, nanomaterial-based insoluble food additives and oral drugs as well as residues of nano-formulated pesticides on plants and nano-formulated animal feed supplements in meat products might present challenges in the EHS domain. While it is unclear if nano-based food additives are being developed in India, titanium dioxide and silicon dioxide nanoparticle additives are already being used in the US albeit in amounts of 1–2 per cent in foodstuffs. Though there is little data available on the possible adverse effects caused by ingested nanoparticles, there is some relationship between chronic bowel diseases, such as Crohn's disease and the dietary sources of nanoparticles (Goswami et al., 2008).

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9 Form I, Rule 6

It now needs to be seen whether the fairly new Indian food safety legislation, the Food Safety and Standards Act, 2006, is able to regulate and address the risks of nanomaterials as food ingredients or additives. The Act was introduced to lay down science-based standards, and to regulate manufacture, storage, distribution, sale, and import of food articles to ensure safe and wholesome food. The Act, a fairly comprehensive one with much emphasis on 'science-based standards', especially in response to sanitary and phyto-sanitary measures agreement and developments at codex, has a number of relevant provisions for regulating use of nanotechnology in food processing and packaging industry, of course with significant amendments.

Under the Act, 'food additive' means any substance not normally consumed as a food by itself or used as a typical ingredient of the food, whether or not it has nutritive value, the intentional addition of which to food for a technological (including organoleptic) purpose in the manufacture, processing, preparation, treatment, packing, packaging, transport or holding of such food results, or may be reasonably expected to result (directly or indirectly), in it or its by products becoming a component of or otherwise affecting the characteristics of such food, but does not include 'contaminants' or substances added to food for maintaining or improving nutritional qualities.[10] Thus, nanoparticles used in packaging can easily be accommodated into this definition of food additives. Under the Act, ingredients refer to any substance, including a food additive used in the manufacture or preparation of food and present in the final product, possibly in a modified form.[11]

Hazard, under the Act means a biological, chemical, or physical agent in food with the potential to cause an adverse health effect.[12] Risk, under the Act refers to probability of an adverse effect on the health of consumers.[13] However, these terms are only with reference to food articles and do not extend to food packaging and such material.

Under the Act, the food Safety Authority can prescribe standards determined on the basis of a risk analysis. Risk management involves taking into account the results of risk assessment which involves the various steps of hazard identification: hazard characterization, exposure assessment,

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[10] Section 3 (k), Food Safety and Standards Act (FSSA), 2006

[11] Section 3 (y) FSSA (2006)

[12] Section 3 (u)

[13] Section 3 (zm)

and risk characterization. One of the main problems in extending this legislation to nanomaterials is the fact that there is lack of sufficient scientific knowledge about nanomaterials and it is not possible to do a reliable risk assessment with the available methodology. However, exceptions are made for developments with uncertain scientific justifications in the form of provisional measures, which could be applicable to nanomaterials. The Act also recognizes 'novel food' for which standards have not been specified. The definition of novel food could be extended to include nanomaterials.

The State Commissioners are empowered to prohibit in the interest of public health, manufacture, storage, distribution or sale of any article of food.[14] They are also directed to carry out survey of the industrial units engaged in the manufacture or processing of food in the state to find out compliance by such units.

The Act may have certain promising provisions but these can be put to use only if there exists greater technical expertise and information to make the use of the space that these provisions offer.

7.5.2 *Occupational Health and Safety*

In India, occupational health and safety is primarily governed by the Factories Act of 1948 and touched upon by a few more legislation.

Under the Factories Act, 1948, the occupier[15] is under a duty to safeguard health, safety, and welfare of all workers while they are at work in the factory.[16] He is also entrusted to ensure that the premises are free from risks to health in connection with the use, handling, storage, and transport of articles and substances, and provide for maintenance or monitoring of such risk-free working environment.[17]

There are opportunities within the Act to address OHS risks from nanotechnology, owing to its broad mandate. At this stage, when all

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[14] Section 30 (2)(a)

[15] An occupier is the person who has ultimate control over the affairs of the factory. [Section 2(n)]

[16] Whereon ten or more workers are working, and in any part of which a manufacturing process is being carried on. Manufacturing process refers to any altering, repairing, ornamenting, finishing, packing, oiling, washing, cleaning, breaking up, demolishing, or otherwise treating or adapting any article or substance with a view to its use, sale, transport, delivery or disposal. [Section 2 (k), (m)]

[17] Section 7(A)(1)

the risks are not yet known, information flow is crucial. The Act specifies provisions for removing the informational gaps, which could lead to occupational health threats. While in general all occupiers have to ensure availability of information, instruction, training, and supervision with regard to risks, occupiers of a factory involving any hazardous process are under an obligation to maintain accurate, up-to-date health records of the workers exposed to any chemical, toxic or any other harmful substances.[18]

The legislation defines 'hazardous process' as any process or activity in relation to an industry specified where, unless special care is taken, raw materials/finished products/by-products/wastes would (*i*) cause material impairment to the health of the persons engaged in or connected therewith, or (*ii*) result in the pollution of the general environment. The definition of 'hazardous' process is wide enough to include nanoparticles, but it is restricted to industries in the schedule.

However, what creates problems for extending the reach of this legislation to nanomaterials is Section 41F which lays down the permissible limits of exposure of toxic substances. The Occupation Exposure Limits (OELs) of particular chemical and toxic substances are determined on the basis of mass concentration and dosages (under Schedule 2 of the Act), while for nanomaterials, other factors might be more relevant to measure toxicity. OELs are generally established after a complete risk assessment, which is not possible for nanotechnology presently. Nanomaterials are also not easily detected by existing instruments and the most optimal parameter to determine the toxicity of nanomaterials is still undefined (Franco et al., 2007).

There are a few other legislations which have a bearing on occupational health and safety in India. One of them is the Manufacture, Storage, and Import of Hazardous Chemicals Rules, 1989, promulgated under the Environmental Protection Act, 1986, which lays down certain responsibilities of the authorities responsible for manufacture, storage, and import of hazardous chemicals. It would be useful to look into how these Rules define 'hazardous chemicals'. With the suggestion being mooted that nanomaterials should be treated as a 'new' chemical, this legislation becomes very important.

Part I, Schedule I of the Rules describes three kinds of hazardous chemicals — toxic chemicals, flammable chemicals, and explosives. Toxic chemicals are

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[18] Section 7(A) and Section 41C

defined as chemicals having certain values of acute toxicity and which, owing to their physical and chemical properties, are capable of producing major accident hazards. Oral toxicity, dermal toxicity, and toxicity by inhalation route are defined in terms of dosage and concentration. The dosages and concentration to qualify as extremely toxic or highly toxic do not apply to nanomaterials due to their extremely tiny size, but even a very small dosage could prove to be extremely or highly toxic. Size apart, toxicity of a nanomaterial may be determined by a complex set of different characteristics, such as surface area, chemical composition, coating, shape and route of exposure, etc. Thus, the definition of toxicity has to be amended in order to take care of nanomaterials as a new chemical.

Coming to the second category of hazardous chemicals which are flammable chemicals, the Rules distinguish between flammable gases, highly flammable liquids, and flammable liquids which become flammable with changes in temperature, pressure, etc. The third category consist of explosives which may explode under the effect of flame, heat or photo-chemical conditions or which are more sensitive to shocks or friction. This categorization of flammable chemicals and explosives may create problems for regulatory oversight over nanomaterials. Although insufficient information exists to predict the fire and explosion risk associated with nanomaterials, nano-scale combustible material could present a higher risk than coarser material with a similar mass concentration given its increased particle surface area and potentially unique properties due to the nano-scale. Decreasing the particle size of combustible materials can reduce minimum ignition energy and increase combustion potential and combustion rate, leading to the possibility of relatively inert materials becoming highly combustible (NIOSH, 2009).

Part II of the Rules gives a positive list of hazardous chemicals, which are defined in terms of dosage or content. The problem with such a list is that a non-hazardous chemical like titanium dioxide which is not included in the list, while being non-toxic in the bulk form, might exhibit toxicity at the nano-scale.

Then again, Schedule 2 sets out the threshold quantities for different chemicals in tonnes, while Schedule 3 sets out the threshold quantities for hazardous chemicals, which relate to each installation or group of installations belonging to the same occupier where the distance between installations is not sufficient to avoid, in foreseeable circumstances, any aggravation of major accident hazards. Thresholds in existing legislation are not tailored to the nano-scale but based on bulk material. To fit the context of nanomaterials, these thresholds based on tonnage have to be modified, taking into account not only size but factors, such as surface area, coating, shape, etc.

Further, it would not be wrong to assume that available toxicity tests would not be adequate to gauge the toxicity of nanomaterials and as state-of-the-art develops, new tests will have to be developed.

7.5.3 Environmental Risk Management

The accelerated development and application of nanotechnologies in recent years has prompted concerns over the safety of manufactured nanomaterials when released into the environment. Thus, it becomes indispensable to see whether the environmental legislation in India would be able to manage the risks to the environment and health which could emanate from nanotechnology application. Here, we have attempted a gap analysis of a few pieces of environmental legislation, namely the Air and Water Pollution legislation and the umbrella legislation, the Environment Protection Act.

7.5.3.1 Pollution Control Laws

In India, the Air (Prevention and Control of Pollution) Act, 1981, deals with the prevention, control, and abatement of air pollution in the country.[19] The Act has a two-tier institutional framework comprising central and state pollution control boards. The Central Board is entrusted with functions like collection, compilation, and publication of technical and statistical data relating to air pollution and the measures devised for its effective prevention, control or abatement in addition to preparing manuals, codes or guides relating to prevention, control or abatement of air pollution; and second laying down standards for the quality of air, etc. The State Boards have the power to inspect, any control equipment, industrial plant or manufacturing process and to give, by order, such directions to such persons as it may consider necessary to take steps for the prevention, control or abatement of air pollution.[20]

The scope of the Air Pollution Act is broad enough to include nanoparticles as well, though suitable amendments have to be made. The Act defines 'air

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[19] Section 25, Water Pollution Act

[20] Sec 17 (1) (e), Air Act

pollutant' as any solid, liquid or gaseous substance (including noise) present in the atmosphere in such concentration as may be or tend to be injurious to human beings or other living creatures or plants or property or environment. 'Emission' means any solid or liquid or gaseous substance coming out of any chimney, duct or flue or any other outlet. The problem with applying the law to nanoparticles come from the fact that the permissible amount of air pollutants are determined on the basis of concentration using methods of measurement, which might not be suitable to detect nanoparticles. For instance, the National Ambient Air Quality Standards, notified by the Central Pollution Control Board (dated 11 April, 2004) has recognized respirable particulate matter (size less than 10 um) as a pollutant. Nanomaterials could fit into this category, but with an amendment in the prescribed concentration levels (which presently is 120 pg/m^3), as a very tiny concentration could prove to be toxic in case of nanomaterials. Along with concentration, other factors which could influence the toxicity of nanomaterials have to be taken into account. All these would require substantial changes. Further difficulty would arise due to the lack of methods to measure nanoparticles in the air.

Similar is the case of the Water Pollution Act of 1974. Under this Act, water is considered polluted when it is rendered harmful or injurious to public health or safety, or to domestic, commercial, industrial, agricultural or other legitimate uses, or to the life and health of animals or plants or of aquatic organisms.[21] Any liquid, gaseous or solid substance discharged from any industry, operation or process, or treatment and disposal system (non-domestic) is treated as a trade affluent.[22] In the context of new and emerging technologies, it is the definition of 'new discharge' that deserves attention. 'New discharge' is any discharge, which is not, with respect to the nature and composition, temperature, volume, and rate of discharge of the effluent substantially a continuation of a discharge made within the preceding 12 months.[23] However, similar problems plague the application of this legislation to nanomaterials as in the case of the Air Pollution Act. Nanomaterials are not separately recognized as a trade affluent, the present standards exist with respect to bulk material and are based on concentration levels.

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[21] Section 2 (e)
[22] Section 2 (k)
[23] Section 25, Water Pollution Act

7.5.3.2 Environment Protection Act, 1986

The Environment Protection Act (EPA) of 1986 is an umbrella legislation under which several notifications and rules have been passed and most environmental initiatives in India have been taken. The Act is in the nature of an enabling legislation designed in such a manner that there is space to address any of the environmental concerns by way of subordinate legislation or powers and functions of the designated officials. Even the definitions are broad enough to include as much aspects of environment as possible. Environment includes water, air, and land and the inter-relationship which exists among all three and human beings, other living creatures, plants, micro-organism, and property[24]; also hazardous substance means any substance or preparation which, by reason of its chemical or physico-chemical properties or handling, is liable to cause harm to human beings, other living creatures, plant, micro-organism, property or the environment.[25]

Notifications with respect to standards of quality of air, water or soil, concentration limits of environmental pollutants, procedures and safeguards for the handling of hazardous substances, etc., are within the purview of the central government and have been the basis for many rules and notifications for environment protection. Not only environment protection from pollution, the Act has been used as a tool to regulate technology in the past as well. For instance, regulation of manufacture, use, import, export, and storage of genetically engineered organisms or cells has been notified under the EPA.[26]

This legislation is considerably broad enough to address risks from nanotechnology; however, doing so will require greater awareness and will on the part of the government and officials. The main regulatory gaps identified by a Defra study (2005) with respect to environmental regulation for the products and applications of nanotechnologies apply to India as well, in that thresholds or exemptions under current legislation are not tailored to the nano-scale, current scientific knowledge and understanding of hazards and risks limited, and the absence of reliable and validated methods of monitoring exposure and potential impacts of nanomaterials on human and environmental health.

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[24] Section 2 (a)

[25] Section 2 (e)

[26] Rules for the Manufacture, Use, Import, Export and Storage of Hazardous Micro-organisms, Genetically Engineered Organisms or Cells, 1989

7.5.3.3 Waste Disposal

Although, responsible waste disposal is a part of the overall environmental and health risk management, we have examined the regulatory framework of waste disposal separately, primarily because generation and disposal of nanowaste is perceived to be a great concern in rapid advancement of nanotechnology. (Breggin and John, 2007). The Royal Academy in its 2004 study recognized that the risk of release of nanomaterials would be highest during disposal, destruction, and recycling.

According to Franco et al. (2007), the main problems in management of nanowastes in the EU stem from the fact that nanowastes are being tackled by waste management regulations in a non-specific way. In general, nanoparticles will follow the material or substance in which they are contained and their fate depends on way these wastes are treated, either as factory waste, municipal solid waste, bio-medical waste or recognized as hazardous waste.

The same could apply to Indian legislation as well which has provisions for waste disposal, namely the Factories Act; the Hazardous Material (Management, Handling and Transboundary Movement) Rules, 2007; the Bio-Medical Waste (Management and Handling) Rules, 1998; all of which obliges an occupier to responsibly manage wastes. The Municipal Solid Wastes (Management and Handling) Rules, 2000, identifies municipal bodies as the responsible agency for any infrastructure development for collection, storage, segregation, transportation, processing, and disposal of municipal solid wastes.

The above legislation are broad enough to include nanowaste as well though in order to make these legislation relevant for nanowaste, specific amendments would be required. Definition of 'waste' under the Factories Act, 'hazardous waste' under the Hazardous Material Rules, 'bio-medical waste' under the Bio-Medical Waste legislation and municipal solid waste under the relevant Rules will have to be amended to specifically include nanowaste.

The lack of eco-toxicological data makes it very difficult to state if nano-particles meet the criteria of hazardousness as required under the Hazardous Wastes Rules. 'Hazardous waste' has been defined to include any waste, which by reason of its physical, chemical, reactive, toxic, flammable, explosive, or corrosive characteristics causes danger or is likely to cause danger to health or environment, whether alone or in contact with other wastes or substances.[27] Given the broad scope of these rules, issues in end-of-life treatment of nanoparticles and other nanowaste can indeed be addressed hereunder. However, this would entail explicit inclusion of nanowaste as a hazardous waste. This may require detailed risk assessment and toxicity level study of waste generated out of nanotechnology application. The guidelines for handling of waste has to take into account the characteristics of nanowaste and this too can take place only when there is enough awareness and understanding of the risks on the part of policy makers. Therefore, institutional capacity and coordination is crucial in this regard.

7.6 Conclusion and Policy Recommendations

From the above discussion, it is evident that applying the 'incremental approach' to nanotechnology regulation both in India and abroad is quite problematic. However, a technology which could have such risks on human health and environment cannot remain unregulated. At the same time, it is important that legal regulation avoids the harmful effects of nanotechnologies resting on incomplete risk information, without casting the incomplete information in permanent law and the key question is how the regulation can be flexibly adjusted to continuously improved risk identification and assessments (Schummer and Pariotti, 2008). There is some apprehension that 'hard' law developed today in the face of grave uncertainty, may end up regulating the field far beyond the period of the law's efficacy.

In such a scenario, the incremental approach holds out some promise and offers a reconciliation between the two schools — one advocating no regulation at present given the uncertainty and the other propounding a stand-alone regulation for nanotechnology. An incremental approach and 'soft law' provisions will help regulatory approaches to keep pace with developments in technology and changes in society to ensure that regulation becomes a 'process and not an event'. The European Commission, Health and Consumer Protection Directorate General (2004) has pointed out that such an approach will help.

> Avoid preventable risks and hazards, taking practical steps to avoid potential hazards and risks when scientific evidence is not complete and still being assembled.

[27] Section 2 (1)

Set up a framework within which (a) stakeholders including scientists, industrialists, and citizens can participate in shaping the course of nanotechnologies, and (b) nanotechnologies can develop safely.

Monitor the development of nanotechnologies by acquiring and generating the relevant data, keeping the possibility of future regulation in future open and making sure that such regulation would rest on more complete data and a deeper scientific understanding.

This holds equally true for a developing country like India, beginning to engage in nanotechnologies, which will help balance the need to promote R&D as well as build capacity to address risks though a risk-based regulation. For India, which is yet to take concrete steps towards regulating nanotechnology, the following could be vital steps in this direction:

- **Regulatory phasing**: Brownsword in *Rights, Regulation, and Technological Revolution* (2008) discusses the concept of regulatory phasing. Accordingly, regulation can be first phase, second phase, third phase, and so on. In the first phase, regulation is meant to control ex ante a particular aspect of practice. In the later phases, this ex ante control is abandoned and operates ex post 'to compensate for or adjust to the consequences of a practice that cannot be controlled by first phase regulation'. Applying the concept of phasing in formulating a regulatory regime for technology holds merit in the Indian context. Different levels of technology development and knowledge would entail a phased response in terms of regulation to respond to situations and concerns as they evolve.
- **Regulatory flexibility**: Regulatory flexibility refers to 'the opportunity to propose and apply flexible regulatory approaches based on demonstration of enhanced product knowledge and process understanding' (Chen, 2007). Since, nanotechnology is an emerging technology, the regulatory actions and instruments to manage the risks should be flexible. A cautious and exploratory approach would be much more feasible and practical at this stage of the technology. Although the concept of regulatory flexibility is often used only in the context of implementation and enforcement, flexibility is an approach that is key in designing the regime as well. And it is in this respect that the flexibility in

regulation of nanotechnology has to be maintained, so as to respond to challenges as they surface.

- **Regulatory interaction**: Any of the abovementioned (or any other) concepts cannot be helpful in an effective regulation, until and unless there is a proper channel of communication amongst the key stakeholders and players. By regulatory interaction, we refer to interaction, exchange of information and concerns between the state and the industry, state and the research community, state and the consumers, state and the civil society. More importantly, the interaction has to take place within the government, among institutes, departments, ministries and units of government, without which the regulatory regime would always be inadequate and little more than a patchwork.

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CHAPTER 8

Capabilities and Nanotechnology Development: Developing Country Perspectives

Manish Anand

The importance of S&T in economic growth and social development is well understood. But the process of building S&T capabilities, which enables countries to engage successfully in scientific research and harness its benefits towards economic growth and development, requires further investigation. A grounded understanding of S&T capabilities for development purposes assumes greater significance in the context of developing countries that are engaged in 'catching-up' or 'leapfrogging'. This may enable developing economies to compete effectively in an increasingly globalized marketplace and overcome their relative underdevelopment. However, development of such capabilities is a challenge in developing countries as there is always a continual emergence of new S&T developments. It is pertinent in this context to gain insights into the process of capability building and understand the capability requirements in the context of an emerging technology, such as in this case of nanotechnology.

8.1 Understanding S&T Capability

The dictionary meaning of capability is the 'ability to or skill to do something'.[1] With respect to S&T, capability could be explained in terms of an S&T system having the attributes needed for performance or accomplishment encompassing the depth and breadth of scientific and technological areas. It would denote the ability to harness S&T for production of commercial innovations that also have societal relevance.

To harness the benefits of new technologies requires a minimum of S&T capability in choosing, acquiring, generating, and applying technologies. Technological capability building has been the focus of interest for more than two decades and the concept has evolved over years (Bell, 1984; Dahlman and Westphal, 1982; Katz, 1987; Lall, 1987; Scott-Kemmis and Bell, 1985). Westphal, Kim, and Dahlman (1985) defined technological capabilities as the 'the ability to make effective use of technological knowledge…. It inheres not in the knowledge that is possessed but in the use of that knowledge and the proficiency of its use in production, investment and innovation.'

The concept of technological capabilities emerged in the context of maintaining competitiveness in a changing environment. Bell and Pavitt (1995) referred to technological capabilities as the 'domestic capabilities to generate and manage change in technologies used in production, and these capabilities are based largely on specialized resources…need to be accumulated through deliberate investment — a management problem'.

However, capability approaches that focused solely on the aspect of generation of knowledge had some generic problems associated with them. Emphasizing only the knowledge generation aspect may not yield the desired result expected out of an S&T activity. A greater need to link knowledge generation to production of socially desirable outcomes was felt by policy planners and those engaged in S&T activities. Kim (1997) emphasized the process of creation of knowledge at the international level by focusing on firms in emerging economies. According to him, technological capability is 'the ability to make effective use of technological knowledge to assimilate, use, adapt, and change existing technologies. It also enables one to create new technologies and to develop new products and processes in response to the changing environment'.

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[1] *Collins Essential English Dictionary,* 2nd Edition 2006.

Enos (1991) put forward a macro perspective of the concept and practice of technology capability. According to him, there are three fundamental components of technology capability, viz., individuals embodying skills, training, and experience and inclination; institutions within which individuals are assembled; and a 'common purpose' defined in terms of objectives and motivations. Further, technological capability can vary between sectors and at various levels of aggregation — micro, sectoral, and macro. For example, in the industrial sector, the elements of technological capability — production engineering, manufacture of capital goods, and R&D — are different from those essential for the services sector (Dahlman and Westphal, 1981). In general, the factors determining/influencing technological capabilities in developing countries are adequate number and quality of human resources with practical experiences, skills, and aptitude; useful technological information on sources and conditions of technology transfer; institutions for education and training, R&D, and engineering design and consultancy; and favourable natural environment and factor endowments, attitudes and customs, etc. (Fransman and King, 1984).

One of the major concerns in the S&T debate is how to integrate scientific resources with the rest of the economy and what are the competencies and institutions that are required to put the knowledge that is being generated into effective use (Hall, 2002; Chataway, James, and Wield, 2005). Since its conceptualization, technological capabilities have taken into account the aspect of generation of technological knowledge and its organizational dimension, i.e., the use of stock of technological knowledge. Contemporary literature emphasizes on the role of institutions as central to building capabilities for production of knowledge and its effective utilization (Edquist, 1997; Oyelaran-Oyeyinka, 2005). The role of institutions — understood as norms, habits, and rules — in determining the way people relate to each other, their learning behaviour and the ability to utilize the knowledge had been insisted upon by Johnson (1988). This is important from a capability perspective in terms of determining the rate and direction of innovative activities. In this regard, capabilities can be best understood with respect to the contextual settings in terms of the institutions and its role in effective deployment of S&T resources.

The concept of capabilities of countries and firms to innovate has evolved over the years. In the process, it has gained a lot from evolutionary economics literature (Nelson and Winter, 1982). Various ideas on capabilities have found coherence in the concept of innovation systems, which looks at innovation — viewed conventionally as a linear process driven by research — in a systematic, interactive, and evolutionary way, whereby networks of organizations, together with institutions and policies that affect their innovative behaviour and performance, bring new products and processes into economic and social use (Freeman, 1987; Lundvall, 1992; Edquist, 1997). Processes of technical and institutional innovations are characterized by co-evolution, interaction, and mutual adjustment (Werle, 2011).

Adopting such a systemic approach of innovation as a network of institutions may help in identifying strategic needs and weaknesses, and would thus be of importance from the perspective of building capabilities. One limitation of the systems of innovation approach is that it tends to be quite abstract and skeletal, providing a conceptual approach to understanding how organizations and institutions involved in R&D, product development, and marketing relate to each other (Chataway, James, and Wield, 2005).

Lall (1992), while linking technological capabilities and innovations, has emphasized the role of national technological capabilities. According to Lall (2000):

> [N]ational technological capability is…more than the sum of capabilities of individual firms in a country. It is an innovation system, which includes the externalities and synergies generated by the learning process, ways of doing business, and the knowledge and skills residing in related institutions.

The acquisition, nature, and development of national technological capability is affected by intervention by government in providing a suitable incentive regime, particularly trade policies and domestic industrial policies. Also, the government plays an important role in skills generation, availability of finance for technological activities, and access to information, all of which constitutes the factor market. Further, government intervention in terms of institutions supporting industrial technology such as, education and training, standards, metrology, technical extension, R&D among others, influences national technological capabilities.

There are reports (Royal Society, 2004) highlighting the importance of both S&T and capacity building. Also, the issue of weak S&T base of the South and its weak integration with production has been dealt upon in detail earlier (Bell and Pavitt, 1993; Garrett and Granqvist, 1998; Ernst, Mytelka, and Ganiatsos, 1998; Forbes and Wield, 2002; Lall, 1990). Developing economies, according to Wong and Brahmakulam (2002), have limited S&T capability and have a weak and fragmented capacity for innovation. This hinders widespread application of new knowledge and its potential to bring about economic growth. According to them, there are many barriers affecting S&T capability on a sustainable basis in developing countries, such as shortage of human and institutional capacity; unfavourable economic policies restricting competition; and lack of political will to implement reforms, maintain stable policies, enforce laws, and pursue good governance. In lieu of scarce resource availability and competing demand for finite resources, they have suggested that for sustained capability building, governments must adopt a long-term vision for making public investment decisions.

Sagasti (2004) opines that building S&T capabilities is a Sisyphean task and the rapid evolution of frontier scientific research and technological innovation erodes and erases the hard-won achievements, even makes insignificant, in building science, technology, and innovation capabilities. According to him, faulty adoption of policies and decision making by policy-makers and politicians has destroyed research and innovation capabilities built over years in developing countries. He emphasizes the importance of mobilization of knowledge and innovation for development and argues that developing countries should pursue capability building for the creation, acquisition, and utilization of knowledge through judicious investment of scarce resources. This should be done without ignoring the heritage of indigenous knowledge and techniques. Comparing the developed and developing economies on the capability front, Sagasti explains that the close and continuous interaction among science, technology, and production led to the creation of an endogenous scientific and technological base in the developed countries. This enabled them to modify, adapt, and recombine existing knowledge, which could be then deployed to produce goods and services. Through learning-by-doing and learning-by-using, the utilization of knowledge and technologies in the productive sector leads to incremental technical innovations. This also leads to accumulation of technological capabilities in the productive sector and to new areas for scientific research. Developing countries, on the other hand, were not successful in their endeavour to establish an endogenous S&T base. In these countries, an exogenous scientific and technological base was developed, which reflected few interactions among modern science, technology, and productive systems with their indigenous and traditional counterparts.

Despite growing literature on capabilities, the concept has not been dealt with in a sufficiently integrated way. Not much attempt has been made to link science, technology, and institutional innovative capabilities with social development (Pettit and Wheeler, 2005). Further, the literature on S&T capabilities has also not focused much on how societal context on one hand shapes technological innovation and on the other how it influences the ability to find solution. In this regard, a deeper understanding of local capability, need, and market becomes important. Fabayo (1996) has stressed on the need to adapt capability building to specific needs and goals of different countries and regions. This chapter while developing a capability framework for emerging technologies in the context of developing countries, views capability as a multidimensional concept and attempts to draw together the various segregated perspectives on capabilities, so as to gain a wider and holistic understanding.

In this regard, building capabilities has to be viewed as a continuum across the entire chain of knowledge generation, utilization, and commercialization. There could be various approaches to building capability in the chain; for example, investments in research and scientific capability, investments in non-scientific skills, creation of enabling environment for the generation and application of knowledge, development of linkages, strengthening the policy process, strengthening stakeholder engagement, and bringing about institutional changes.

8.2 Why Is a National Capability in S&T Important?

Capability in S&T holds special significance as it enables countries to produce and innovate rather than becoming a mere user of goods and services. It is well established that if developing economies could effectively harness a portion of the technologies presently available globally, they can rise in the ladder of socio-economic development. However, technologies need considerable effort to be accessed, mastered, adapt, and used efficiently. This calls for a conscious effort to build capabilities.

Also, capability in S&T would enable countries to address their developmental needs such as developing low-cost technologies in areas of sanitation, healthcare, energy, nutrition, elementary education, and housing. Although several advanced technological options in the above mentioned areas might already exist, they must be customized to local conditions. To undertake such a task would require the existence of a certain degree of capability.

Furthermore, with trade liberalization and rapid technical changes, developing countries want to have access to new technologies to compete in world markets. However, new technologies may require higher skills and involve technical and organizational demands. This may pose a challenge to developing economies in engaging with these technologies and deriving benefit from it. This underscores the importance of developing capability. Moreover, it has been observed that within the developing world, countries that have effective capability-building processes are able to perform better than those that have not (UNIDO, 2002). This also explains that building capabilities is a continuous and cumulative process and countries have different levels of capability.

In what follows, the kinds of demands created by an emergent technology, such as nanotechnology, on the S&T system of a developing country is examined.

8.3 Nanotechnology and Its Application Potential in Developing Countries

Nanotechnology refers to the development and application of materials, devices, and systems with fundamentally new properties and functions because of their structures in the range of about 1 to 100 nanometres (nm) (Siegel et al., 1999). It involves the manipulation and/or creation of matter at the nano-scale at which the characteristics of the matter changes significantly because of properties such as the dominance of quantum effects, confinement effects, molecular recognition, and an increase in relative surface area (Renn and Roco, 2006). Some materials and processes in nature are also this small. However, what makes nanotechnology different is that it is based on the recent ability of humans to consciously engineer materials and machines at the tiny scale of 100 nm or less. In addition to size, nanotechnology is also exciting because many nanomaterials have new, never seen before properties. Downsized material structures of the same chemical elements change their mechanical, optical, magnetic, and electronic properties, as well as chemical reactivity leading to surprising and unpredicted, or unpredictable, effects (Renn and Roco, 2006). Thus, an existing material, on a nano-scale, can be transformed to have different properties, opening new technological possibilities.

8.4 S&T Capabilities: Key for Engaging with Nanotechnology

To realize the actual application potential of nanotechnology would depend largely on capability, at the national level, to successfully engage in the emerging domains of S&T. This would pertain to the ability of existing S&T institutions to engage with such technologies; industrial competence in undertaking the task of technology selection, classification, adaptation, and exploration; availability of financing; a proper understanding of the market structure and function; ability to design and implement S&T policies; as well as the ability to address challenges to convert research into technology and development within suitable legislative and regulatory frameworks.

Although the above-mentioned capability requirements are generic and are significant for any emerging technology, however the nature and characteristics of nanotechnology offers some distinctive challenges. Nano S&T research work has to be carried out in an interdisciplinary fashion and the nature of technology is quite complex. Because of its highly multi-disciplinary nature cross-cutting many industries and technology chains, nanotechnology reshapes the existing organizational arrangements amongst actors giving rise to new forms of configurations. These pose a significant challenge to the existing S&T system of a country in engaging with such technologies.

Furthermore, nanotechnology, besides offering a wide range of opportunities for development, also raises several ethical and social issues pertaining to risks and accessibility. Therefore, in the trajectory of nanotechnology development—if left to the forces of commerce and competition—the most important questions about nanotechnology pertaining to hazards and risks to human health and the environment may not be posed sufficiently. It may so happen that the benefits are stressed and questions skewed towards issues of sufficiency of investment, profitability, receptivity of markets, intellectual property, speed of innovation, and application (Mehta, 2002). Thus, extending the discourse to include human welfare issues would be important.

In the above context, the process of developing capability with respect to nanotechnology may require reorientation of dimensions characterizing capability. Therefore, it would be important to gain an understanding of the existing S&T capability, and how it needs to evolve to engage with nanotechnology.

8.5 Building S&T Capability

8.5.1 Drivers and dimensions

Building S&T capabilities has to be viewed as a continuum across the entire chain of knowledge generation, utilization, and commercialization. Looking at the actors and the institutional context in which knowledge generation, utilization, and commercialization takes place, the S&T system includes universities and research organizations, private firms — multinational and national — small and medium enterprises (SMEs), industry associations, policy-making bodies, entrepreneurs, non-governmental organizations, supportive structures such as markets and credit, and regulatory infrastructure.

For research to contribute to economic growth, the existence of knowledge base in terms of a critical mass of trained scientific manpower in various areas of S&T having the ability to create, adopt, and apply knowledge is necessary. Investment in research, education, and industry becomes important from this perspective.

Firms can benefit from the existing research and knowledge base and increase their productivity and income. In order to achieve this, firms would have to undertake the task of *adoption* of research results and utilize it in their production process to *develop* technology products. Subsequently, *demonstration* and *deployment* of the developed technological products and its successful *commercial launch* in the market will have to follow. Various factors such as policies, human resources, infrastructure, market conditions, and business practices would influence the performance of these activities.

The market plays an influential role in shaping the trajectory of technology development. The presence of an efficient factor market leading to competitive capabilities, the labour market providing the new skills needed, the financial market providing the capital to finance learning, and the technology market providing the information needed to master a new technology, becomes important from the perspective of building capabilities (Lall, 2006). Any capability-building exercise should satisfy the end result of socio-economic development. For this, the technology products being created need to be taken to the market for user adoption. Users' adoption of knowledge and tools would be influenced by market demand, cultural preferences, and access to finance among others (Wong and Brahmakulam, 2002). In this regard, it is important to distinguish that putting products on shelves, i.e., deployment, is different from its market acceptance. This suggests the importance of market reforms for adoption of a new technology by users (Wong and Brahmakulam, 2002).

In Figure 8.1, the linkages between various components denote that the traditional linear understanding of knowledge transfer from basic research to production and commercialization have been replaced by non-linear models of innovation flow composed of several actors and interactive learning. The feedback loop underscores that S&T development is a dynamic process and it is important that research and innovation activities are relevant to the market. In this regard, the framework for S&T capability has to be viewed both as a system and process. It is a system since the existence of inter-linkages and knowledge flow among the heterogeneous set of elements would be crucial. Further, building S&T capability is a continuous process as there are always opportunities and demands on the anvil, thus requiring a constant

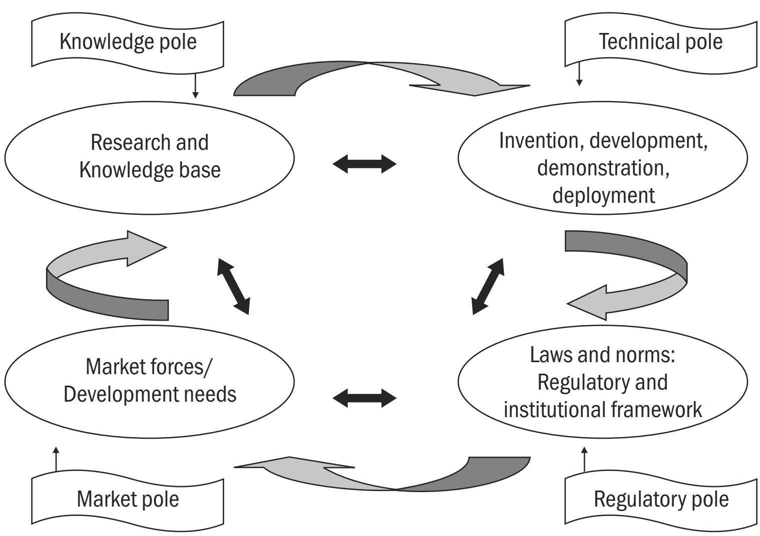

Figure 8.1: The interactive S&T base of drivers, systems, and responses

redefinition of strategies and policies on the part of various actors to engage with them.

The four poles of *knowledge*, *technology*, *regulation*, and *market* drive the process of S&T capability building. The knowledge pole embodies the research and knowledge base which determines the pace and direction of S&T within a national boundary. The competence level in the existing knowledge domains can act as a stimulus for engaging with emerging technologies. The technical pole characterized by the ability to produce new goods and services also impinges upon the innovation process. The degree of penetration in existing technological fields and the breadth of technical areas covered would enable countries to venture into emerging technologies. The technological level of industry and production would characterize this. The third driving force is the market pole, which relates to demands of goods and services by users and customers. The regulatory pole includes legislations and secondary rules and also includes government policies. However, it is important to make the caveat that in one sense the regulatory pole would underline all the other poles in as much as separate sets of laws and regulations would be operational to enable the functioning of each of the other poles. Thus it is important to delimit the ambit of this pole. The subject area of the regulatory pole largely relates to environment, health and safety, production and marketing, consumer protection, producer responsibility and product quality, and waste disposal laws and regulations. The pole will also include institutions that are an important part of the structural framework enabling the implementation and functioning of the legal regime.

S&T capability can have different dimensions. For instance, existence of robust scientific organizations such as universities and public and private research institutes signifies *organizational* capability. Innovative firms for effective utilization of the knowledge being generated in scientific and research institutions furthering the process of technology development connote *enterprise* capability. A technically and scientifically skilled workforce constitutes the *human resource* capability. Capability relating to formulation and implementation of effective S&T policies is of overarching significance, as by encouraging stable investment in human and institutional resources to adopt, adapt, apply, and develop new ideas and technology, it maximizes its effect on economic development. Policy also has an important role in facilitating linkages among organizations, improving information flow, and exchange between private and public sectors and strengthening institutions that facilitate innovation. Another important dimension of capability is the sufficient and timely availability of *financial* resources to support S&T. Last, but not the least, the existence of social institutions, which actively respond to S&T developments, constitutes an important dimension of S&T capability.

8.5.2 Capability dimensions and their characterization in the context of nanotechnology

8.5.2.1 R&D

The process of building S&T capabilities requires the existence of robust scientific organizations — universities, and public and private research institutions — wherein knowledge, having potential for technological innovation is being generated. Production of knowledge in universities and research institutions via R&D is an important dimension determining capabilities. Also, the academic system is the major source of human resources development in S&T.

Nanotechnology has been accorded national R&D priority in both developed and developing economies. This is evident from rapidly increasing government investment in R&D in this area. Given its vast application potential in diverse areas, such as, health, energy and environment, agriculture, materials, etc., nanotechnology forms an important part of national S&T agendas in these sectors. At the international level, the thematic areas of nanomaterials, nanoelectronics, nanobiotechnology, nanoanalytics, and nanophotonics are of considerable importance with regard to nanotechnology R&D.

Although the national R&D strategies of countries may vary, some key trends could be deciphered globally. This may be important from the perspective of building capabilities in developing economies.

The requirement of nano centres has been acknowledged globally and as a result specialized centres in the field have started to spring up. This is mostly to harness the potential of the emerging discipline of nanotechnology and to effectively address issues of risk and establishment of best practices and standards. The present focus is on widening the knowledge base and of monitoring development to devise effective strategies in the future.

International networks are emerging as the locus of innovation in the international nanotechnology landscape. Also, there is an increasing trend of partnerships involving public sector research institutes, private sector, and the government. Specialized research centres in nanotechnology are being established by leading countries in nanotechnology serving as incubators for innovation. Further, there is a global focus on development of instrumentation and standards to successfully harness the potential of this emerging technology.

Young and highly dynamic fields of S&T, such as nano S&T, which are interdisciplinary in nature, would require S&T organizations to work in an interdisciplinary mode. Many research breakthroughs in nanotechnology are stimulated in the intersection of established scientific disciplines and across fundamental and applied technological research. For instance, consider that organizational infrastructure dedicated to the fundamental understanding of certain nano-scale properties (basic research) is institutionally separated from the organizational infrastructure for modifying the nano-scale phenomenon (applied technological research). Therefore, inter-institutional collaboration, combining scientific knowledge from various disciplines in universities and laboratories, is an important dimension of performance in the emerging field of nanotechnology. This may pose quite a challenge to traditional institutions and the preparedness and the ability of S&T organizations to overcome these would greatly determine its capability to tap nanotechnology. Further, the ability to tap global knowledge base by forging international partnerships can go a long way in effectively harnessing this technology in the context of developing economies.

For developing organizational capability in nanotechnology, establishing new multi-disciplinary research centres in nanotechnology, starting Centres of Excellence (CoE) in existing S&T institutions, and national consortia on R&D in nanotechnology, consisting of different nanotechnology R&D institutions could be advantageous.

As discussed earlier, nanotechnology may pose significant risks to human health and the environment. Therefore, developing research capabilities in risks and safety aspects would be key to ensure that the human welfare discourse is taken into account in the quest for harnessing nanotechnology.

Since, technologies are socially embedded, understanding the socio-economic implication of any technological intervention is important. Deciphering the ethical, legal, and social implications, in the context of emergent technologies, assumes great significance in today's world. It calls for developing social science research capability to undertake research in such areas.

8.5.2.2 Technology development

Tracking international nanotechnology developments it could be observed that there is a strong focus on the commercialization of advancements already made in R&D. Further, there is a growing interest of various economic enterprises in nanotechnology. As nanotechnology has cross sectoral applications, firms depending on their capability are making decisions regarding whether to focus on one technology or market structure or cross boundaries between different nano-scale technologies.

Firm-level case studies in the UK (Chilcott, Jones, and Mitchel, 2001; Meyer and Morlacchi, 2003, cited in Meyer 2006) and Germany (Tisnado, 2005; Meyer, 2001, cited in Meyer, 2006) have shown that firms rarely cross boundaries between different nano-scale technologies, such as nanoparticles, nanostructured films or nanocomposites.

Further, looking at the way firms and industry dynamics are unfolding in nanotechnology, Palmberg and Nikulainen (2006) have observed that there are a large number of start-ups, which have sprung up in this field, besides the existing firms who have tried to incorporate nanotechnology in their production processes. They indicated that 'top–down' nano-scale engineering approaches are more likely to enhance the capabilities and knowledge base of incumbent firms. As such, large established firms in end-product industries — chemicals, electronics, forest-based, and metal industries — would be able to harness nanotechnology. However, for an incumbent firm to make transition from an old technology to a new technology would be determined by the characteristics of the new technology, such as its complexity and socio-economic benefit, capital intensiveness (it can be supplied by small firms), radical nature so as to inhibit investment by large firms concentrated on existing technologies, among others. On the other hand, 'bottom–up' nano-scale engineering approaches might favour new entrants over large incumbents.

Nanoscience and developments in nanotechnology are expensive and require cooperation between industry and research institutions. Industry–academia interaction in nanotechnology appears to be of great significance due to the need to translate nanotechnology research into products and services having market potential. To enhance academia–industry interaction in nanotechnology, several strategies have been adopted; for example, tax incentives, financial support for small business and start-ups, formation of networks in nanotechnology, and funding of collaborative projects. Japan is promoting successful industrialization of nanotechnology through projects aiming at enhancing technology transfer from academia to industry and providing incentives, such as prioritizing research funds, for effective collaboration between industry, academia, and government.

According to Meyer (2006), since nanotechnology has cross sectoral applications, firms will have to undertake strategic decisions whether to (*i*) occupy a technological niche and apply their proprietary technology to one specific application area; (*ii*) build on a base in several nanotechnology areas, and by integrating technology and expertise in more than one nanotechnology area, develop solutions for one area of application; (*iii*) pursue an approach that champions customizing expertise and technology to a range of different application areas; (*iv*) or combine expertise in more than one nanotechnology with more than one application area.

Further, nanotechnology, being expensive and complex, would require greater collaboration between industry and academia. However, the flow of knowledge from research institutions to an industry is not an easy matter. In developing countries, there is not much interaction between industry and academia. This would pose a significant challenge to the developing countries in its ability to harness the benefits of nanotechnology. In this regard, the transition of academic knowledge into the commercial sector would require several factors, such as excellent research results, managerial and industrial competence, and financial support, among others.

Also, the ability of a firm to produce new or improved products, processes, and services is dependent on other dimensions of capability like financial investment and human resources in R&D and academia–industry linkages. The role of policies in shaping the firms' learning behaviour becomes crucial. Policies on trade, competition, and labour affect the learning of firms by way of the signals it receives from the market (Lall, 2006). Also, institutional factors, such as the intellectual Property Rights (IPR) regime has a great influence on the choice of innovation in firms, which need to take decisions — on whether to ahead with indigenous R&D or source technology from outside. At the same time, business practices and social capital gains importance by way of affecting firms interaction pattern with each other and the way they respond to government policies (Lall, 2006). Thus, enterprise capability has to be viewed in relation to its linkages and dependence with other dimensions of S&T capability.

8.5.2.3 Financing

Sufficient and timely availability of funding to support developments in S&T is another very important dimension of capability. Funding is required across the innovation chain starting from knowledge generation, utilization, and commercialization. Looking at the global scenario in nanotechnology funding, countries have used different mechanisms to coordinate R&D activities at the national level. For example, France, the UK, and the USA have a central coordinating body with funding mechanisms specific for nanotechnology. While Canada, China, Ireland, Italy, and Japan provide funding through existing national funding and research mechanisms under a consultative body in the government, Germany and South Korea provide funding through individual ministries and agencies.

As R&D is a high risk and capital-intensive activity, existence of a suitable financing mechanism could be a key factor for the growth of industrial R&D. Availability of early stage investment capital would be an important factor that will determine the commercialization of R&D. Internationally, venture capital funds provide seed capital for start-ups, and new R&D projects are funded by special purpose vehicles (EXIM Bank of India, 2006). However, in developing countries such mechanisms are either non-existent, or are at a very nascent stage. Thus, to engage with emerging technology would require support from public funds, venture capital, special investment funds as well as multilateral and bilateral support funding. For transformation of research outputs of S&T organizations in nanotechnology into commercial ventures, there is a need to encourage venture capitalists in forming partnerships with R&D labs.

8.5.2.4 Human resources

Developing human resources capability is an important dimension of the capability-building process for advancing innovation activities and generating productivity. For technology-intensive R&D, availability of qualified researchers, scientists, and engineers is very important.

Emerging technology requires constantly upgraded skills and competencies across the entire innovation chain, starting from performing R&D in the lab to working at the firm level. An interdisciplinary-oriented workforce capable of working in the area of nanotechnology would be necessary. In this regard, imparting education in nanotechnology at the undergraduate, post-graduate, and higher levels could be a step forward.

Providing training to the scientific staff in this emerging technology could be another step, which could be undertaken. However, there is a need for a change in the manner in which scientists are trained in frontier S&T areas. Instead of confining the training to only the technical specificities, it should also involve imparting training in complementary skills, such as IPR, building partnerships, among others. This would help in gaining a wider view of the work and in undertaking collaborative work.

Insufficient human resources in R&D — both in public and private sector research institutions — and their quality are a constraint, particularly in the settings of developing economies. In developing countries, there has been a decline in the number of students opting for research in basic sciences. In the context of nanotechnology, which derives its strength from basic science research, such trends may pose considerable challenge. In this regard, generating academic interest in basic as well as applied sciences and providing financial support to attract and retain science and engineering student could be adopted towards building talented manpower.

Further on, entrepreneurial capability acting, as a medium in the transfer of technology from the point of generation to the point of utilization, is also an important element determining capabilities, especially when the rate of technological change is rapid.

8.5.2.5 Policy systems and process

Building S&T capability is a long and cumulative process (Juma and Konde, 2002) and besides scientific and research institutions and laboratories, stable investment in human and institutional resources to adopt, adapt, apply, and develop new ideas and technology is required. In this regard, S&T policies are imperative to encourage such investment and maximize their effect on economic development.

The government has played a predominant role in the research effort in establishing the scientific and technological infrastructure. To effectively harness the potential applications of nanotechnology, countries around the world have devised strategies and undertaken policy initiatives. Inter-ministerial bodies have been established to provide guidance for policy development. In countries such as the US, China, Japan, and South Korea, there are interagency coordinating offices under the offices either of the prime minister or president. Further, policies on nanotechnology aimed at enhancing cooperation and partnerships between organizations, addressing challenges to convert research into technology by improving information flow and exchange between the private and public sectors, have been undertaken in countries that are forerunners in the field of nanotechnology in the world. Also, policies to facilitate innovation and technology diffusion by strengthening institutions have been devised by leading countries in nanotechnology in the world.

As nanotechnology has application potential in several sectors, each having different needs operating over divergent time scales and exposed to different market dynamics, countries have also developed or are in the process of developing sector-specific strategies and policies.

In the context of developing countries the role of S&T policy, besides deciding the level of investments and prioritization of sectors, the level of importance attached in engaging with the ethical, legal and societal dimensions — all requiring a substantial amount of funding — would enable a smooth and healthy penetration of nanotechnology within a national boundary. Also a critical issue in the policy-making process would be the development of capacity in the usage and maintenance of advanced products using cutting-edge technologies, such as nanofilters, nanophotovoltaic cells, and the like. Given that nanotechnology has application potential in various sectors of the economy, development of cross-sectoral policies for nanotechnology may be a critical approach to the capability-building process.

8.5.2.6 Societal interface

Science and technology are not independent variables and the interaction between science and society takes place within a particular socio-economic context. Questions pertaining to when and how societies should take decisions about regulating, developing, investigating, and investing in technologies needs to be properly addressed to strengthen S&T capability.

Emerging technologies may need new regulatory approaches and legislative mechanisms because of its size, environmental spin-offs, and disposal. When current legislation proves insufficient, there is a need for either specific legislation and regulations for nanotechnology or adapting existing legislations as per the demands posed by an emerging technology. To customize existing legislation, several countries have, as a first step, focused on developing appropriate monitoring and warning systems. However, there are some important caveats regarding changes in legislation.

While designing regulatory policies, the changes being made should facilitate innovation rather than being restrictive. Also, the period of regulatory uncertainty should not be too long.

In the context of nanotechnology, the issue of risk is of prime importance. The small size and the new physical and chemical properties and functions of nanosystems may pose diverse risks resulting from their interaction with human and natural systems. The risks may have national as well as global repercussions in terms of economic imbalances and widespread environmental contamination. Studies on nanotechnology have indicated the lack of information about the human health and environmental implications of manufactured nanomaterials and issues of safety concerns pertaining to emerging technologies have been raised (Michelson, 2004).

Accordingly, the area of risk governance in nanotechnology becomes significant. Risk governance includes the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analysed and communicated, and management decisions are taken (Renn and Roco, 2006). Risk governance is an important concept for assessing and managing the implications of nanotechnology in the context of the relationship among new technologies, risk, and sustainability (ETC Group, 2003; Burke, 2003). Renn and Roco have identified the deficits of the risk governance system for different nanotechnology generations. Low level of knowledge of the new properties and functions on toxicity and bioaccumulation, limited understanding of the nanomaterials exposure rates, and gaps in the regulatory systems at the national and global levels are the main deficits of risk governance for the first generation of passive nanostructure (nanoparticles, coatings, and nanostructured materials). While for the second, third, and fourth generations of nanoproducts (including active nanodevices, nanobiotechnology applications, and nanosystems) the main deficits include, uncertain/unknown evolution of the technology and human effects as well as a framework through which organizations and policies can address such uncertainties.

Although several projects addressing Environment, Health, and Safety (EHS), including toxicology, workers safety, and ecotoxicology, as well as standards, nomenclature and patenting, have been initiated in different countries around the world in the last few years; however, the area of risk governance has not been given adequate attention.

Given the importance of risk research in nanotechnology, developing countries having limited resources have to prioritize between funding research for commercialization and risk research. Although the nature of risk would be similar for nations engaged in the pursuit of nanotechnology development, the extent of exposure of these risks to populations would be largely determined by the institutional capacity of countries indicated by dimensions, such as existing regulatory mechanisms, communication policy, stakeholder participation in establishing and reviewing safety standards, and the like. Developing economies in order to engage with nanotechnology should enhance capabilities on the above dimensions pertaining to risk governance and urgently address the gaps in research and policy making in the area.

8.5.2.7 Stakeholder engagement

Multi-stakeholder interaction in S&T, involving civil society and community organizations and media among others, becomes crucial from the standpoint of efficient technology development and deployment, responsible and sustainable technology development, and greater commercialization success. However, to successfully do so would require responsiveness and flexibility on the part of the S&T organizations, enterprises, and policy-makers towards these issues.

Social institutions such as civil society organizations (CSOs) can play an important role in the alignment of research priorities to that of development needs of a country. With their field-level experiences, CSOs can support the scientific community in setting up of research priorities. A wider understanding of the policy dimensions, which are increasingly becoming complex in the wake of globalization and IPR developments, requires developing certain degree of capability in these areas. Some of the CSOs work actively on these policy areas and have developed international linkages, which helps them in gaining quick access to international developments and agreements. Therefore, CSOs can provide crucial inputs in policy making relating to the likely impact of international S&T developments on the domestic sector.

Further, CSOs can provide a better understanding of various policy developments including those related to IPRs in nanotechnology, as and when they emerge, and also on international developments related to framing of issues related to risks of nanotechnology.

8.6 Towards Developing a Conceptual Framework to Assess National Capability to Respond to Nanotechnology Developments

A conceptual framework to assess national capability to respond to nanotechnology development needs to address the key opportunities and challenges created by this technology for developing countries in terms of the demands imposed on the S&T infrastructure and by changing the nature of S&T. International developments in nanotechnology indicate the following:

- There is a need for strong infrastructure to enable and stimulate R&D and commercialization of nanoproducts
- Constraints and concerns among users must be addressed for successful deployment of technology
- Appropriate strategies, policies, and institutions are needed to engage with an emergent technology
- Human resources with multidisciplinary perspectives is key for progress in nanotechnology
- There is a need for addressing nanotechnology risks in the societal context
- Regulatory oversight for nanotechnology is necessary to channelize research efforts in a specific direction
- Transparency and public involvement in the design and implementation of regulatory structure in nanotechnology should be ensured

Developing capabilities in emerging technologies thus would require: (*i*) skills of both scientific and non-scientific kind; (*ii*) a greater degree of linkage between various actors from academia, industry, policy-makers that would be necessary for the successful market deployment of such technologies; (*iii*) interdisciplinary approaches in nanotechnology that would demand a different R&D strategy as well as reorientation of S&T activities in universities, research institutes, funding agencies, and industry with a conducive institutional setting facilitating interactive learning would be essential to respond to and develop nanotechnology; (*iv*) devising adaptive and responsive governance structures that can suitably regulate applications of nanotechnology in society; and (*v*) a flexible and dynamic policy environment that has the ability to create the conditions required for both knowledge generation and its effective utilization which would form an important dimension guiding the process of development of capabilities (Figure 8.2).

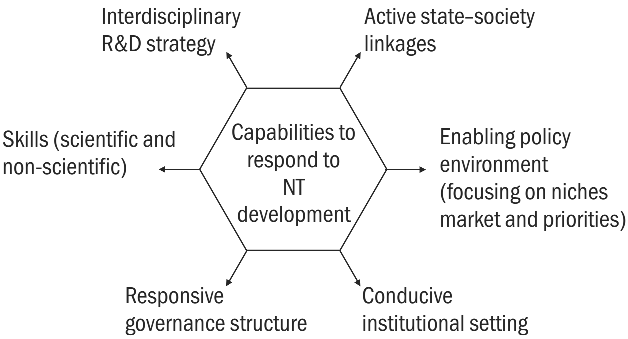

Figure 8.2: Capabilities to respond to nanotechnology developments

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CHAPTER 9

Nanotechnology in India: A Case for Multi-level Governance

Nidhi Srivastava, Manish Anand

Poised to be one of the 'defining technologies' of the 21st century with envisaged breakthroughs in a large number of fields, nanotechnology has fuelled a significant increase in R&D expenditure in several developed countries. Developing countries are also increasingly investing in nanotechnology, in view of its potential as a key tool for addressing key development-related challenges in sectors, such as energy, water, agriculture, health, environment, and the like. However, the very same attributes that make nanotechnology so unique and endowed with immense potential for both societal benefits and economic gain, also pose questions regarding its safety and carry social, economic, ethical, and other implications. This poses considerable challenges for governance of nanotechnology, with the governance framework being required to reconcile the need to provide a nurturing environment for the development of the technology and maximize societal benefits, while addressing the risks and socio-economic implications.

9.1 Issues in Governing Nanotechnology

In recent times, the governance of emerging technologies, such as nanotechnology offering 'radical new solutions' has engendered considerable political, legal, and ethical debates. Fiorino (2006) acknowledges that growing complexity, dynamics, and diversity of our societies, as caused by these rapid technological and scientific developments, put governing systems under much strain and required the formation of new conceptions of governance from a one-way to a two-way traffic between the public and the private. While 'governance' of nanotechnology has most often been used in the context of risk considerations, there is a need to view it from a much broader perspective. While governance of risk is imperative, benefits and opportunities also constitute an important aspect and the two always need to be balanced against each other (Weidmer et al., 2010). A governance framework for nanotechnology has to address simultaneously the need to provide a nurturing environment for the development of the technology and maximize the societal benefits, while addressing the risks and socio-economic implications.

Issues in evolving a governance framework for nanotechnology are manifold, the main being to ensure a certain level of safety without acting as an impediment to development and stifling innovation. This is compounded by the fact that there is considerable scientific uncertainty regarding the risks which nanotechnology could pose to health and environment, the unavailability of metrology tools, the absence of standardized methodologies for risk assessment and management, difficulties in developing regulation in the face of such uncertainty, etc. These problems are magnified for developing countries lacking the resources as well as the capacity to engage in risk research, assessment and management, and development and implementation of regulations, while being severely constrained by the lack of standards. Davies (2009) found that most developed countries including the US have limited regulatory preparedness for nanotechnology and apprehends that this would become more problematic with the next generations of nanotechnology as the already existing gap between capabilities of the regulatory system and nanotechnology developments would only become wider. Apart from the environmental and health impacts, nanotechnology could have major impacts on the existing social, economic, and trade milieu of developing countries, which needs to be addressed in a 'responsible' governance framework, but have not been adequately studied.

9.2 The Case for Multi-level Governance in Nanotechnology

There has been some realization that rapid technological and scientific developments typical with nanotechnology has put governing systems under much strain and require new conceptions of governance. There is a need to move away from the 'government' approach characterized by a top–down legislative approach, to a 'governance' mode characterized by increased participation and cooperation between the different players and stakeholders. It is in this context that this chapter seeks to build the case for the development of a multi-level governance framework for nanotechnology in India and suggests ways and means on how to achieve it. Originally developed in the context of developments in EU policy in the 1990s, the concept of multi-level governance (MLG) has since then been accepted in theoretical discourses on governance in general and extended to various issues and jurisdictions. The MLG approach, as developed by Marks et al. (1996), is characterized by 'the existence of overlapping competencies among multiple levels of governance and the interaction of political actors across those levels'. The key elements of MLG include increased participation of non-state actors in government functions, shift from discrete territorial levels to complex overlapping networks, change in the understanding of the state's role from command and control to co-ordination, steering and networking, and a shift in the way democratic accountability in governance takes place. It can be of two types — vertical and horizontal. The former refers to dispersion of power to jurisdictions at different territorial scales ranging from international to local. On the other hand, horizontal MLG is a scenario where jurisdictions cut across Type I territorial scales and are defined in terms of the tasks they perform rather than a generalized approach. Neither type alone is sufficient on its own. Inter-linked, they comprise the framework of MLG together.

9.3 MLG: The Conceptual Framework

Governance can be broadly described as the body of rules, enforcement mechanisms, and corresponding interactive processes that coordinate and bring into line the activities of the involved persons with regard to a common outcome (Fischer, Peterson, and Huppert, 2004). According to Florini (2008), the term encompasses but goes beyond governmental functions to include the agenda setting, negotiation, regulatory, implementation, and monitoring roles that are sometimes played by businesses or civil society actors. Jollands et al. (2009) define governance not as a concept but an approach or perspective to governing process. Given that such an approach involves several actors, issues, and interests, it must recognize the existence and importance of overlapping and competing authorities at different scales (Bulkeley, 2005), including 'glocalization' (Swyngedouw, 2003).

The all-encompassing nature of governance makes it impossible to be restricted to a particular level, region or domain. However, governance has typically had a top–down approach with little interaction across scales. There has been a thrust on multi-actor and multi-level governance as a more inclusive, coherent, and participatory option as against a top–down approach of governance (Kern and Bulkeley, 2009). The concept of multi-level governance tries to weave together all the different scales existing around an issue by actors with different interests and values.

In the context of developments in EU policy in 1990s, Marks et al. (1996) developed an MLG approach characterized by 'the existence of overlapping competencies among multiple levels of governance and the interaction of political actors across those levels' (Marks et al., 1996). Since then, the concept has been accepted in theoretical discourse on governance in general and extended to issues and jurisdictions beyond the EU. Over the last two decades, the MLG concept has been contextualized in various spheres and jurisdictions. Environmental governance is one such area, where the discourse on decentralization has been complemented with a broader multi-level governance approach (Bulkeley, 2005; Homeyer and Knoblauch, 2008). With globalization, there has been a proliferation of jurisdictions and emergence of non-state actors, territorial boundaries have become blurred, and the global is more connected to the national and local.

In recognition of the fact that externalities of policies and government actions transcend territorial boundaries, and necessarily vary from global to local, MLG seeks to internalize these differences in externalities. To this effect, "governance must operate at multiple scales in order to capture variations in the territorial reach of policy externalities" (Marks and Hooghe, 2004). It therefore addresses complexity at and between levels going beyond a linear approach to the study of international organizations on national polity and on specific thematic areas (Stubbs, 2005).

It is not possible to have a universal definition for the concept of MLG but Bache and Flinders (2004) outline key elements of MLG:

- Increased participation of non-state actors in government functions;
- Shift from discrete territorial levels to complex overlapping networks;
- Change in the understanding of the state's role — from command and control to coordination, steering, and networking; and
- Shift in the way democratic accountability in governance takes place.

A MLG framework can operate at both vertical as well as horizontal levels. The former relates to a distribution of functions and responsibilities across different hierarchical jurisdictions — international, national, state, and local. The latter, i.e., the horizontal level is a more complex arrangement where overlapping jurisdictions interact with each other across levels. The interactions among several actors occur horizontally beyond the hierarchy of institutions and could include inter-ministerial, inter-departmental, state and non-state interactions. These interactions transcend not only territorial and administrative boundaries but different policy spheres as well.

According to the classification by (Hooghe and Marks, cited in Bache and Flinders, 2004), there are two types of multi-level governance: Type I refers to dispersion of power to jurisdictions at a specific number of clearly defined general purpose jurisdictions — from international to local. Conversely, Type II is a scenario where jurisdictions cut across Type I territorial scales and are defined in terms of the tasks they perform rather than a generalized approach. In a Type I model of governance, there are non-intersecting and non-overlapping jurisdictions. There is a nested hierarchical structure, explained by its proponents through a metaphor using Matryoshka dolls, where:

> [E]very citizen is located in a Russian Doll set of nested jurisdictions, where there is one and only one relevant jurisdiction at any particular territorial scale. Territorial jurisdictions are intended to be, and usually are, stable for several decades or more, though the allocation of policy competencies across levels is flexible. (Hooghe and Marks, cited in Bache and Flinders, 2004)

These would thus refer to governments and authorities at international, regional, national, state, local, and rural levels where each of the units have broad-ranging identical powers and responsibilities without any overlaps in the responsibilities for a given territory and population (Moore, 2003). Here, authority is spread over a flexible and fluid collage of overlapping jurisdictions.

Type II refers to task-specific specialized jurisdictions, characterized by flexibility, varied scales, and no limit on the number of jurisdictional levels and actors. Often there will be intersecting memberships and implementation, given the focus on tasks as against pre-determined territorial limits.

Kern and Bulkeley (2006) propose another approach to analysing MLG through the modes of governance focusing on: (*i*) authority; (*ii*) provision, (*iii*) enabling provisions and actions; and (*iv*) self-governance. Jollands et al. (2009) have suggested yet another approach to MLG and they identify scope, structure, and budgetary allocations as the factors integral to its understanding. Irrespective of the approach within MLG and the elements of analysis, what is distinct about MLG framework is that it goes beyond movement through a set of nested scales from the local to the national to the international, but local politics can directly access other relevant local actors in the same country and abroad (Sassen, 2003).

With all its proposed benefits, a MLG approach is fraught with several challenges. Literature identifies these limitations as being too descriptive (Bache et al., 1996) and lacking a clear conceptual focus (Peters and Pierre, 2004). Another challenge has been balancing actors and coalitions with structures and instruments of governance. The actor-centred approach must deal with relations between state actors at levels as well as relations across sectors (Bache, 2008). These limitations and challenges would have to be addressed while devising MLG framework for any sector, including nanotechnology.

9.4 MLG Framework for Nanotechnology Governance in India

Nanotechnology, like any emerging technology, has promising potential benefits as well as uncertainties about the impact it can have on human health, environment, markets, and society. This is what makes most of the new technologies quite contested when released. The fact that this uncertainty gets aggravated and becomes an issue of concern in nanotechnology is what distinguishes it from other technologies introduced previously. Paddock (2009) identifies these as the fast pace and large scale of developments, diversity of technologies involved, promise of potential benefits along with limited knowledge about impacts and nature of risks. These factors make the fabric of nanotechnology governance more complex with a greater role for a diverse set of actors and stakeholders in this area. This makes governance of nanotechnology difficult through conventional linear approaches and calls for a multi-level approach to governance to ensure that the technology is developed in a way that it contributes towards societal benefits in a responsible manner. Figure 9.1 summarizes the vertical and horizontal dimensions — through an actor-based approach as well as issue-based approach — in MLG of technology.

9.4.1 Vertical

Vertical dimensions of MLG refer to the interaction amongst different levels of actors. These are marked by clearly defined hierarchical jurisdictions where there is a distribution of powers and responsibilities. The vertical interaction is very similar to the theory of federalism. Multi-level governance systems, however, are more likely to be 'pervasive, almost omnipresent, political units in today's highly complex, ideologically divergent, and increasingly globalized world' (Stein and Turkewitsch, 2008).

Since nanotechnology is characterized by multiplicity — of disciplines and technologies involved, uses, areas of application, actors and even challenges — it is difficult to study the vertical dimensions without focusing on a given sector. This chapter provides a general comment on developments,

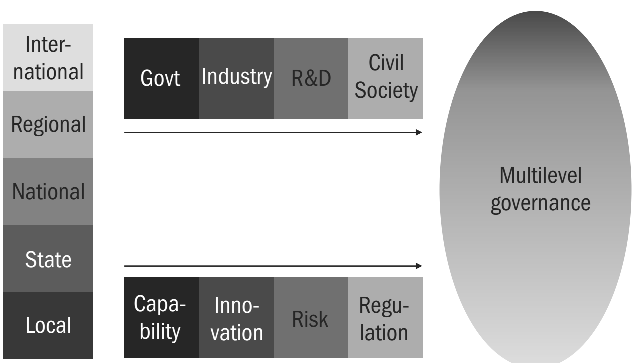

Figure 9.1 Technology governance

characteristics, and challenges, and particularly deals with the health or medical applications for studying vertical governance patterns on account of its relevance for a developing country like India. It looks into investments and interests and its direct impact on human health.

In the case of nanotechnology applications in the health sector, a governance framework, including the vertical dimension, must aim at both the above mentioned dimensions of technology governance. The levels of governments or institutions, which can be included in a MLG framework, is important not only to make the governance inclusive and democratic but also because the number of actors determines how complex the framework would be (Jollands et al., 2009).

The following sections map the different actors at different levels having a role in governance of technology, how they interact with each other, and how they influence the nanotechnology landscape in India and in medical applications in particular.

9.4.1.1 International

In a vertical analysis of MLG, governments across levels — from local to provincial to national to international — are examined. However, a MLG framework for nanotechnology needs an assessment of sub-political and apolitical sites as there has been a growing trend towards the acceptability of international forums/institutions as efficient and effective sites of regime creation. Some of the important and active sites are characteristically sub-political in nature in as much as they lack effective legitimacy and formal rule making or implementation power.

International regimes such as the WTO would apply to nanotechnology like any other technology, whether it is to do with trade or intellectual property rights. With respect to intellectual property rights, the role of international bodies in shaping the domestic regimes has been rather strong, given the binding commitments under WTO. The role of TRIPs and its influence on the pharmaceutical sector has been discussed and debated extensively across forums (Barpujari, 2010).

In the case of health, the role of World Health Organization (WHO) is central as it garners acceptance by countries and institutions and hence, there is legitimacy of its definitions, decisions, and directives. One of the founding mandates of WHO is to 'develop, establish and promote international standards with respect to food, biological, pharmaceutical and similar products' (Article 2, WHO Constitution). To this effect, the Department of Essential Medicines and Pharmaceutical Policies at the WHO develops guidelines, builds capacity, and promotes medicine safety through pharmacovigilance at global, regional, and country level. No action is currently being taken specifically on nanotechnology as yet, except through its intergovernmental forum on chemical safety.

The Intergovernmental Forum on Chemical Safety (IFCS), International Standards Organization (ISO), and the International Risk Governance Council (IRGC) are three sites that need special mention for their sub-political nature in the context of nanotechnology. Norms emanating from international sub-political sites have earlier had an influential role in domestic regime creation. Given that the Indian domestic regime for nanotechnology is still at a nascent stage and essentially reactive in nature, the deliberations within the aforementioned sites could have considerable influence in the governance of nanotechnology in India.

In today's world where states and actors are connected at multiple co-existing levels, internationalization of regulation is a concept, difficult to avoid. The influence of this internationalization could be on account of commitments at international forums, interdependence amongst countries in terms of research, application and markets, increasing acceptability of international standardization process. We have seen this earlier in the case of food safety regulations (Srivastava and Chowdhury, 2008).

9.4.1.2 National

At the national level, the Ministry of Science and Technology is the nodal ministry for promotion of R&D in the area of technology and administers its functions through three departments — Department of Science and Technology (DST), Department of Biotechnology (DBT), and Department of Scientific and Industrial Research (DSIR).

The DST has been the most instrumental agency within the government for encouraging nanotechnology development and application through both financial and institutional support. In 2001, a Nano Science and Technology Initiative (NSTI) was launched and as a follow up to it, the Nano Mission was set up in 2007 for basic and applied research promotion, infrastructure support, education, and international collaboration in this regard. The department provides the secretariat to the Nano Mission Council, which is the highest advisory policy-making body for nanotechnology in India, along with two other advisory groups, viz., Nano Applications and Technology Advisory Group and the Nano Science and Advisory Group.

The DBT and DSIR too have been supporting some research in nanotech, although not in an organized manner. While DBT has focused essentially on nanobiotechnology research, most of the nano research funded by DSIR pertains to materials and metals and chemicals.

Institutes and laboratories under the Council for Scientific and Industrial Research (CSIR), such as the Central Drug Research Institute (CDRI) and the Indian Institute of Toxicological Research (IITR), are engaged in crucial and specialized research fundamental for nanotechnology governance.

The Ministry of Commerce and Industry, especially the Department of Industrial Policy and Promotion (DIPP), aims at facilitating investment and technology flows in industrial development. The Office of the Controller General of Patents, Designs and Trade Marks is also a part of the DIPP thus making the Ministry of Commerce an important actor in protecting intellectual property rights in the field of nanotechnology and being responsible for addressing the complexities of nanotechnology in the current patent legislation.

Given that most of the R&D and applications are taking place in the health sector and products are being launched in the market, the role of the Ministry of Health and Family Welfare (MoHFW) is very important. However, unlike the Ministry of Science and Technology, there is no special nano programme in the profile of MoHFW. Research in health-related applications, including nanotechnology based, is promoted through the Indian Council of Medical Research (ICMR), which has a mandate to direct research funding in areas of national health importance.[1] The MoHFW is involved in governance of nanotechnology applications in health sector through the Directorate General of Health Services, under which the Central Drugs Standard Control Organisation (CDSCO) is situated. Health being a state subject is largely in the domain of state governments, but a lot of the direction for the same comes from the centre. Institutionally, MoHFW is incharge of prevention and control of health-related hazards, but the agenda of MoHFW is already full with issues like providing basic health infrastructure; eradication of diseases like polio, kala azar, etc.; and check counterfeit drugs to lay priority on nanoapplications

[1] Projects primarily dealing with research on nanomaterial use for drug delivery have been funded by the ICMR. See, ICMR (2006–07)

in health sector. Moreover, the current health applications in nanotechnology are more focused towards curative applications[2] rather than public health.

The Ministry of Environment and Forests (MoEF) deals with environmental impacts or hazards emanating from a new application. The Central Pollution Control Board (CPCB) discharges most of the functions relating to prevention and control of pollution, including through hazardous materials.

Central institutes under the Department of Pharmaceuticals, Ministry of Chemicals and Fertilizers, are engaged with advanced studies and research in pharmaceutical sciences, including toxicology. They also have the mandate for conducting programmes on drug surveillance, community pharmacy, and pharmaceutical management.

9.4.1.3 Sub-national

At the central level, the Controller General of Patents, Designs and Trade Marks under DIPP is in charge of patents. The legislation and policies on patents are made at the national level — with a great amount of international influence — but patents are filed, examined, and granted at one of the four patent offices located in Delhi, Mumbai, Chennai, and Kolkata. State governments also invest in nanotechnology R&D.

Most of the centres of excellence or research institutes working on nanotechnology are funded or supported by the central government. However, states have a role to play in promotion of R&D and providing infrastructure and other required resources for promotion of research and development in the field of nanotechnology. These research institutes and laboratories also provide the institutional support required for the discharge of regulatory functions of state-level agencies for health and environment.

The CDSCO is responsible for drugs approval and laying down standards but the implementation takes place at the level of states and union territories. There are 35 State Drug Controllers (SDCs),[3] which have the primary responsibility of overseeing the regulation, manufacture, sale, and distribution (including licensing) of drugs (Section 18 of the Drugs and Cosmetics Act, 1940). In their tasks, the SDCs are guided by the CDSCO and aided by government analysts and drug inspectors.

[2] Even the amongst the curative applications, most offer solutions for diseases such as cancer, diabetes, cardiac problems, etc., rather than malaria, tuberculosis, and so on.

[3] The list of State Drug Controllers is available at http://cdsco.nic.in/html/STATE%20DRUGS1.htm (last accessed: March 2013).

State Pollution Control Boards (SPCBs) are the state-level authorities under the Environment Protection Act. The SPCBs do not look at nanotechnology applications or health applications. However, any commercial establishment or manufacturing process will have to adhere to standards laid down by the EPA and Hazardous Materials Rules, thereby bringing them under supervision of SPCBs. The State Pollution Control Committees are responsible for granting authorization for collection, reception, storage, treatment, and disposal of bio-medical waste.

9.4.1.4 Sub-state

In the overall governance framework for any technology, either with respect to environmental impact or health impact, there is a limited role for local authorities. This is ironical as the impact of an emerging technology percolates down to the lowest levels. Drug inspectors and health and sanitation inspectors monitor and operate at local levels also. Local authorities can take *suo motu* action in case of a public nuisance (including risk to environment and human health) being caused by a technology developer or a manufacturing process. This is of utmost importance as the impact of any technological introduction will be felt locally. Local authorities and stakeholders may not have had a say in the decision-making process for development as well as regulation of technology but it is pertinent to note that several products are launched on 'pilot scale' at local or rural levels.

9.4.2 Horizontal

The horizontal dimension of MLG operates at two levels, between actors at the same level/within jurisdictions and another based on issues (Figure 9.1). In a technology governance framework, the three most important issues are that of (*i*) capability and innovation, (*ii*) risks, and (*iii*) regulation.

9.4.2.1 Capability, Technology Development, and Innovation

The role of policy instruments in building science, technology, and innovation capability is paramount. Policy instruments comprising measures aimed at building institutions and capacities to produce scientific and technological knowledge, and also to recover and upgrade traditional knowledge and techniques; promoting the utilization of the knowledge generated in the country in production and service activities; strengthening the linkages between the supply and demand of knowledge produced; and actions to strengthen S&T policy-making capabilities need to be defined and applied to harness benefit from S&T and successfully engage with emerging technologies (Sagasti, 2004). Of late, there has been a growing surge in interest in developing countries in engaging with the various policy instruments. Some of the policy instruments available to policy and decision makers to establish science, technology, and innovation capabilities in developing countries are enlisted in Table 9.1.

Table 9.1: Governance tools to build science, technology and innovation capability

Category	Type of policy instruments	Specific Measures
Building science, technology, and innovation capabilities in developing countries	Supply side: creating S&T institutions and building research and technology development capacities	Creation and consolidation of all types of S&T institutions, financing of S&T activities, human resource development, S&T foresight and planning, creation of networks of institutions
	Demand side: promoting the utilization of domestic S&T knowledge in production and service activities	Strategic planning of production and service activities, financing of innovation at the firm level, use of the state's purchasing power, technical norms and standards, fiscal incentives to stimulate innovation, promoting export of technology intensive goods
	Linking the domestic supply with the demand for S&T knowledge associated with innovation in the productive system	S&T parks and incubators, technology extension services, engineering design and consulting services, selective recovering and upgrading of traditional techniques, policies to promote technology diffusion between firms, cluster policies to link technology leaders with other firms

Contd...

Table 9.1: Contd...

Category	Type of policy instruments	Specific Measures
	Strengthening S&T policy making	Creation of specialized S&T policy agencies, coordination of national and local initiatives in S&T, organize policy research and foresight centres, provide information to policy makers
Creating linkages between knowledge, technology, and production in developing countries and their global counterparts	Establishing linkages with the world scientific research community	Joint research projects, access to international S&T information, remote access to research facilities and equipment
	Obtaining and securing access to external sources of technology	Purchase of technology intensive goods and services, technology licensing agreements, utilize intellectual property regulations, technology scanning and search
	Establishing linkages with the global production system	Direct foreign investment, import and export of equipment and machinery, trade in goods and services, subcontracting in global value chains
Establishing a favourable context and institutional framework for creating an endogenous S&T base	Providing the physical infrastructure for the performance of scientific research, technology development, and innovation	Communications facilities, transport infrastructure, reliable energy supply, clean water and sanitation, waste disposal, clean air, appropriate land-use regulations
	Establishing institutional arrangements favourable to innovation	Elimination of bureaucratic impediments, transparency, fair and effective regulatory agencies, prevalence of the rule of law, democratic governance

Contd...

Table 9.1: Contd...

Category	Type of policy instruments	Specific Measures
	Creating a stable economic policy framework conducive to long-term thinking in firms and other organizations	Price, interest rate and exchange rate stability, sensible financial and credit policies, prudent fiscal policies, tax arrangements that encourage investment, openness to trade and investment
	Evolving a cultural and social environment that encourages creativity, risk-taking, and innovative behaviour	General and scientific education, fair and flexible labour policies, environmental protection, access to information and freedom of the press, poverty and inequality reduction, punish corruption, encourage trust and build social capital, promote values congruent with modern S&T and entrepreneurship
Source: Sagasti (2004)		

Innovation in nanotechnology may be conceptualized as the accumulation and diffusion of scientific knowledge in research institutions and firms. Innovative activities involve directly or indirectly a large variety of actors, including firms, research organizations, such as universities and public and private research centres, financial institutions, regulatory authorities, consumers. Institutional environment may facilitate the interaction among various actors and the emerging policy options would have to be explored for application of new technologies in the production processes with special focus on institutional environment. New products, processes, and services created using nanotechnology involve social, economic, ecologic, political, and ethical matters surrounding their emergence. All this needs to be sufficiently addressed in defining the nanotechnology innovation trajectory.

Establishment of research infrastructure in universities and public-funded R&D bodies, development of human resources for research and industry has been spurred by government initiatives and policies in the health sector. Human resource development in this area has witnessed an increase over years but still there are concerns regarding the quality. Also the availability of researchers trained specially in nanotechnology remains limited. Indian firms also demonstrate capability in performing R&D and production of innovative health products. To further broaden their cost-effective manufacturing capabilities, firms have started investing in new manufacturing facilities.

Tracking developments in nanotechnology applications in the health sector in India, it could be observed that most of the current initiatives are focused towards the curative aspects of health research. However, there has been policy focus in the area of public health research. It is important to note that the wider coverage of public health area necessitates action on the part of several actors and policy-making bodies. For instance, research in the area of clean drinking water should not only be in the purview of MoHFW but also of Ministry of Water Resources.

The DST is the main body in India providing the financial and institutional support for the promotion of nanotechnology development and application. Beside DST, the Department of Biotechnology has been supporting research in the area of nanobiotechnology. The Department of Scientific and Industrial Research (DSIR) too has been promoting research in materials, metals, and chemicals. The Defence Research Development Organization (DRDO) is also engaging with nanotechnology and has come out with diagnostic tools for tuberculosis and typhoid using nanotechnology. The governance circuit also reaches beyond the state actors and includes non-state actors, such as firms, industry associations, civil society, etc.

In addition to the government agencies, industry associations have also showed keen interest in the area of nanotechnology health applications. For example, the nanotechnology initiative launched in 2002 by Confederation of Indian Industries (CII) focused at R&D in bionanotechnology, drug discovery, and delivery by forging partnerships and collaborations. Similarly, the Associated Chambers of Commerce and Industry in India (ASSOCHAM) is trying to explore nanotechnology application potential in the pharmaceuticals, FMCG, and electronics sector.

The requirement of establishing specialized centres in the field of performing transdisciplinary R&D of instrumentation and standards to successfully harness the potentials of this emerging technology has been felt and focused upon, accordingly. Initiatives are being undertaken to maximize the socio-economic and humanitarian benefits to the local people by bringing S&T capabilities from around the world into a local ecosystem which engages local people.

9.4.2.2 Risk governance

Risk can be defined as 'an uncertain consequence of an event or an activity with respect to something that human's value' (Kates et al., 1985). It refers to both the likelihood of certain consequences from specific activities, and the severity of such effects (Renn, 2005).

As discussed in Chapter 4, there exist multidimensional risks around nanotechnology ranging from environment and health and occupational risks to socio-economic risks. A holistic approach to risks is essential and nanotechnology risks can be best understood in conjunction with its benefits. A technology governance framework should also address the risk of missing an opportunity that the technology can offer.

Currently, the ethical, legal, and social aspects of nanotechnology do not feature much in the concerns around nanotechnology and its applications. The current focus is on Environment, Health, and Safety (EHS) from a nanotoxicological as well as occupational health and services (OHS) perspective (Weidmer et al., 2010). However, parallel approaches emphasizing building capacity in both scientific methods and sociological approaches to risk assessments must be prioritized.[4]

Exposure pathways to nanotechnology products are multiple, and effectively monitoring them becomes a daunting challenge since these exist along the manufacturing and consumption chain.[5] Risk concerns in nanotechnology are dominated by complexity, a high degree of uncertainty, and lack of adequate and clear knowledge about the response of humans to nanotechnology applications (Renn et al., 2006).

Risk governance is focused on the institutional arrangements of how risk information is collected, analysed, and communicated and how risk management decisions are taken (Renn, 2005). The IRGC framework for risk governance integrates scientific, economic, social, and cultural aspects and includes the effective engagement of stakeholders (IRGC, 2005). It is the most

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[4] Stakeholder dialogue on 'Issues of Risk in Regulation of Nanotechnology', organized by TERI on 8 January 2010, New Delhi.

[5] This has also been highlighted by our study of issues involved in life cycle analysis of nanosilver based candle filter. It emphasizes upon the need for studies on the nature and degree of nanoparticle exposures from nanoapplications, their toxicity, fate and persistence, simultaneously with technology development. See Chapter 4.

comprehensive risk governance framework for nanotechnology comprising following steps:

- Pre-assessment
- Risk appraisal
- Characterization and evaluation of risks
- Risk management
- Risk communication

Besides, integrating laws, policies and institutions at all these above mentioned stages, an inclusive risk governance framework would entail democratizing science by strengthening the involvement of all the relevant actors and stakeholders (TERI, 2009; Vivekanandan, 2009; IRGC, 2006).

In recognition of the fact that nanotechnology is still an emerging technology which has the potential to address several needs and demands from various sections of the society, rapid developments are being made in pushing for greater application of nanotechnology across fields and sectors. However, little is being done in terms of formulation or assessment of risks associated with nanotechnology research and application in different fields. Even the governments have been focusing on promotion of nanotechnology application without giving due consideration to the risk aspects of the same.

In view of such a scenario where the formal political agenda[6] is also inclined towards promoting nanoapplications and meeting their needs through the intervention of new and emerging technologies, there is a clear role for a sub-political site such as IRGC which can put risk governance on the table as an agenda that needs to be recognized, discussed and made part of the overall policy framework for nanotechnology in domestic and international regimes. This does not imply that the advantages being offered by technology are rejected, as that itself would also amount to a loss. Therefore, a cautious approach should be taken and a risk governance system should be put in place so as to avail the benefits that a new or emerging technology offers. It is also important that international bodies coordinate in terms of their work on nanotechnology. For instance, ISO has a subcommittee to examine the health and environment safety practices; OECD and IFCS too deal with impacts of nanotechnology. It is important that developments

[6] The main government programme for nanotechnology is mission mode and has a clear agenda of promoting nanotechnology in India.

at these forums are in tandem with each other. Thus, besides the inter-level coordination, as discussed in the section on vertical MLG, intra-level coordination forms the core of MLG.

At the national level, the need for this interaction and coordination holds even more weight due to multiplicity of actors and issues of legitimacy. Risks being context specific, there is a pressing need for active risk governance at domestic levels. Risks to environment and human health have been identified as a primary area of concern in need of immediate action, although other risks have been acknowledged. In this respect, a key challenge is knowledge gap vis-à-vis impacts and levels of exposure.[7] To remove this gap, several actors within and outside government will have to coordinate their activities and share knowledge. The agencies of importance include the DST, MoEF, and MoHFW.

Although most of the research is taking place in the public sector, the role of the private sector is growing with more technologies being transferred to companies for commercialization and products already launched or nearing launch in the market. Through their manufacturing process and marketing, companies can help in risk identification, management, and communication. They can provide valuable data with respect to risks to help in risk assessment and devising the appropriate governance strategy.

9.4.2.3 Regulatory governance

Regulation relates to government action in the form of laws and notifications with the objective of directing private action for a specific purpose or with a certain aim (Brownsword, 2008). Governance and regulation may overlap in terms of their purpose and impact but there is a clear differentiation between the ambits of regulation and governance. The regulatory framework for a technology will refer to a number of aspects of the production and application of that technology (Susskind, 1996). In the specific case of emerging technologies like biotechnology and nanotechnology, given the potentially adverse health (Moore, 2004) and environmental impacts that could result, the most widely publicized policy discussions have been on the question of risk regulation (Fiedler and Reynolds, 1994; Hudson, 2003).

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[7] At the stakeholder dialogue on issues of risk and regulation in nanotechnology, organized under the project, the stakeholders voiced concern about paucity of risk assessment studies and data to aid decision making. See, TERI (2010).

Chapter 7 of the book provides an extensive review of the regulatory regime for nanotechnology applications in health sector. Regulatory instruments and interventions can be classified into five main categories or stages of technology development and application: (*i*) research and development, (*ii*) production and marketing, (*iii*) occupational health and safety, (*iv*) environmental risk management, and (*v*) waste disposal.

There are several regulatory instruments across these stages and there are both opportunities as well as gaps within the existing regime for nanotechnology. In some cases, the gaps outweigh the strengths and opportunities of a rule, whereas in some cases, the opposite is true. Our analysis shows that there exists some level of flexibility within the existing regime to initiate a response to meet challenges related to nanotechnology. However, even to make use of the flexibilities, where available, major steps will have to be taken to put them to use.

9.5 Discussion and Conclusion

One of the chief reasons behind the categorization of nanotechnology as an interdisciplinary technology can be found in technological systems convergence. Given its organic and inorganic applications, nanotechnology is very amenable to convergence processes and hence becomes an enabling technology.[8] As Nordmann notes, 'From the point of view of nanotechnology, what used to be separate domains of biomedicine, information technology, chemistry, photonics, electronics, robotics, and materials science come together in a single engineering paradigm' (Nordmann, 2004). Given that nanotechnology is widespread in its reach and interdisciplinary in nature, it spans issues, domains and stakeholders making it a complex territory for governance. With these characteristics and complexities nanotechnology seems apt for MLG, which itself is going to be more challenging in the case of nanotechnology.

To realize the actual application potential of nanotechnology would depend on capability at the national level to engage successfully in the

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[8] According to Whitman (2006), technology systems convergence is defined as a combination of enabling scientific discoveries (genetics, nanoscience), techniques (informatics, gene splicing), and advances in allied tools (computing power, scanning tunnelling microscopes, robotics) that greatly accelerate the basic sciences involved and their practical applications, across a breathtaking range of subjects, from human health to materials science.

emerging domains of S&T. This would pertain to the ability of existing S&T institutions to engage with such technologies; industrial competence in undertaking the task of technology selection, classification, adaptation, exploration; availability of financing; a proper understanding of the market structure and function; ability to design and implement S&T policies; ability to address challenges to convert research into technology and development of suitable legislative and regulatory framework for such technology. It is also imminent that technology is developed in a way that it contributes towards societal benefits in a responsible manner.

The case of health sector in India shows the need for building capabilities at various levels for technology to contribute towards societal benefits. Capabilities in terms of number of research institutions and organizations in the health sector vary across regions. More concentration of institutions is found at the national level with major cities having large number of research organizations. For example, cities like Bangalore followed by Delhi, Hyderabad, Lucknow, Kolkata, and Mumbai share the largest number of health research organizations. This capability is manifested in terms of these cities having infrastructure facilities, adequate human resource availability, and high inflow of funds.

Capabilities in health services delivery at the district and local level remains weak to a large extent. In the MLG framework, a greater emphasis needs to be laid at the local level. Downstream engagement, right from the framing of research agenda to developing innovative health products and services, would be an essential pre-requisite for effectively governing the health sector.

The R&D system is fragmented with a large number of government structures, organizations, and programmes existing in India. Besides the institutes under central ministries, respective state governments have been actively involved in scientific research and training. However, while, at the central level, there exists several departmental laboratories under professionals with strong and often directed research — both basic and applied along with strong infrastructure — the scenario at the state level is characterized by few labs, multiple goals, often under administrative executive and weak research and infrastructure.

One of the prerequisites of a competent institutional framework is regulatory capacity for formulation of rules, policies and guidelines, and implementing. Any regulatory intervention to achieve the goal of regulation would require a great amount of technical expertise and foresight on the part of policy makers and regulators. The implementing agencies, which are usually at the state and local levels, need to be equipped to execute the rules and regulations that are already in place and are formulated from time to time. The agency responsible for regulation of drugs already faces challenges with respect to capacity in terms of even testing of drugs.[9] Considering the lack of capacity for existing drugs with known risks, it is obvious that regulating drugs with risks yet to be known and defined would be an almost impossible task. Further, known capacity for testing nanoparticle toxicity exists only at a very few institutes such as NIPER and IITR.

Nanotechnology development in India is largely a government-led initiative, yet the state agenda is marred with a serious lack of coordination at several levels — research, policy, and interagency/governmental. The existing linkages between our S&T institutes under the Ministry of Science and Technology and other S&T institutes under the socio-economic ministries and such others that does not appear to be strong and clearly differentiated. Similarly, coordination and linkages between central and state S&T institutes might gain from this learning.

Diverse capabilities, although weak, and wide variance in governance structure characterized by multiplicity of ministries, local governments, and regulators at various levels (central and state), federal law making institutional structure, existence of a sizeable number of public, private, and public–private sector entities coupled with internationalization of R&D is one of the central features of Indian S&T. The huge S&T infrastructure and a federated stakeholders-related governance structure poses challenge as well as offers opportunities and calls for clear delineation of roles and responsibilities at multiple tiers including at local governments for knowledge generation, its utilization, and adaptation.

An outcome of the institutional structure (i.e., the departments' form of agency creation) within the Government of India has been the fracturing of regulatory jurisdiction between agencies. Environmental health is an important area of regulation specifically in the context of the potentially adverse impacts of emerging technologies like nanotechnology and

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[9] As per the *Report of the National Commission on Macroeconomics and Health, MoHFW*, Government of India 2005, only 17 of the SDC agencies had access to drug testing facilities

biotechnology. However, the division of the regulatory mandate between the MoHFW and MoEF has made it difficult to provide comprehensive and coherent regulatory cover on the issue of environmental health. Management of environmental risk comes under the mandate of the MoEF but none of its legislations have identified nanoparticles as a potential hazard and therefore it has no jurisdiction to impose any precautionary measures (Jayanthi et al., 2012). In fact, environmental health as a policy discipline is underdeveloped in the Indian context.[10] Thus, the fragmentation of mandates further exacerbates regulatory fissures in situations wherein the state indirectly undermines regulatory overtures by privileging technology within the development agenda of the state by setting up individual state departments with the sole objective of technology promotion and facilitation (Anand et al., 2012).

Even outside the health sector, nanotechnology applications may raise several health concerns. Risks could be in the nature of occupational health, consumer health, and environmental health. Occupational health is the prerogative of the Ministry of Labour, health is the mandate of the MoHFW, and environment is governed by the MoEF.

A smooth flow of information is necessary for enabling any governance framework and more so if it is multi-level. In the case of nanotechnology with which significant degree of uncertainty is attached given its evolving nature, the staple sets of concerns for governance are further amplified. There exists the concern that in a field where debates on nanotechnology — let alone the regulation — are struggling to keep pace with technological advancements, the possibility of its abuse remains ever present. This concern gets exaggerated with a lack of information about the developments, policies/agendas and most important, scientific knowledge about the risks associated with nanotechnology on human health, environment, and society.

Since one of the main concerns around nanotechnology is EHS risks, governance of which necessitates availability of information, both about the nature and extent of applications as well as the risks associated, it becomes absolutely important that such information is readily available with the governing agencies. This becomes even more crucial because risk and toxicity studies are specialized disciplines, which only a few institutes are equipped

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[10] See for similar conclusions, World Bank (2001)

to carry out and may be beyond the capabilities of regulatory institutions. There is paucity of data and risk assessment studies to guide the risk governance process at present (TERI, 2010). Hence, the information amongst agencies, with different mandates, such as DST, DSIR, MoHFW, Ministry of Consumer Affairs (MoCA), and the research institutes should be channelized in a way that each of the these institutions perform their functions and further their mandate in an informed manner.

It is clear that knowledge sharing is important for discharge of regulatory functions but it has a greater role in shaping the trajectory of technology development. In the absence of adequate knowledge about risks and impacts, there can be assumptions about both the potential benefits as well as risks. One among the many challenges that can potentially influence the ambit and effectiveness of governance institutions in the future is the polarization of the debate on nanotechnology's benefits and dangers. There is a danger of the debate going the biotechnology way in which the supporters and the critics were arrayed at extreme positions on the issue.

As nanotechnology has application potential in several sectors, each having different needs operating over divergent timescales and exposed to different market dynamics, countries have also developed or are in the process of developing sector-specific strategies and policies.

Chapter 8 on 'Capabilities and Nanotechnology Development: Developing Country Perspectives', observed that in the context of developing countries the role of S&T policy, besides deciding the level of investments and prioritization of sectors, the level of importance attached in engaging with the ethical, legal and societal dimensions — all requiring a substantial amount of funding — would enable a smooth and healthy penetration of nanotechnology within a national boundary. Also, a critical issue in the policy-making process would be the development of capacity in the usage and maintenance of advanced products using cutting-edge technologies, such as nanofilters, nanophotovoltaic cells and the like. Given that nanotechnology has application potential in various sectors of the economy, development of cross–sectoral policies for nanotechnology may be a critical approach to the capability-building process.

Technology development as a state agenda has to an extent meant exclusion of other stakeholders from the decision-making and governance process. The considerable leverage given to pioneers of Indian scientific establishment and technocrats has made it difficult for the private sector or civil society to participate in the governance process, which is still government-centric. Recently, the Bt brinjal moratorium may have put civil society at the forefront but it seems like a stand-alone decision. Besides, the legitimacy of that moratorium itself is a subject of debate.

Credibility of policies and actions is central to a wider acceptance and inclusiveness of governance, which is difficult to obtain in view of the divides and differences on basic beliefs vis-à-vis benefits and risks of technology, which itself are rooted in the 'history and symbols of one's culture' and locally constituted perception. (Skogstad, 2002; Beck, 2000) One way of overcoming the problem of legitimacy is through democratization of MLG facilitating a dialogue and learning across state and non-state actors. In India, traditionally science has enjoyed a privileged position in the state agenda and been approached in a national context, however, gaining credibility and legitimacy for MLG of nanotechnology would entail departing from that stance and democratizing science by strengthening the involvement of four key actors — political, business, scientific, and civil society communities.

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