ISSN: 0972-7566

Vol. 15 | No. 3 | November 2013

ASIAN BIOTECHNOLOGY AND DEVELOPMENT REVIEW

Special Issue on Nanotechnology and Nanobiotechnology in Agriculture and Food

Guest Editors: *R. Kalpana Sastry and N.H. Rao*

ARTICLES

Asian Biotechnology and Development Review

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RNI Registration No. DELENG/2002/8824

This journal is abstracted/indexed in CAB International, Elsevier Database and EBSCO host™ database.

Printed at D.K. Fine Art Press Pvt. Ltd., New Delhi

Asian Biotechnology and Development Review

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RIS
Research and Information System
for Developing Countries

Asian Biotechnology and Development Review
Vol. 15 No.3, pp 1-6

Editorial Introduction

R. Kalpana Sastry* and N. H. Rao*

Nanotechnology is emerging as a key technology in many sectors and food and agriculture are no exceptions to that. The very possibility to control and modify material and systems at the nanoscale level enables us to produce materials that are significantly different in characteristics from those found or produced at large scale. In food and agriculture sectors, nanotechnology's potential applications include development of water purification systems, rapid pathogen detection systems, and nano-enabled renewable energy technologies that can be used in both sectors. The range of these nanotechnology based applications cover the entire gamut of food chain including packaging and storing food products. In the last two decades, R&D in nanotechnology has grown rapidly in public and private sectors while many countries including the USA and India have launched national level initiatives in nanosciences and technology. Given the potential of nanotechnology and regulatory issues, many organisations including OECD, FAO are working on regulation and governance of nanotechnology.

The technological convergence of nanotechnology with other technologies like biotechnology and Information and Communication Technologies (ICTs) opens up many opportunities for wider application of nanotechnology in food and agriculture. At the same time, realising their potential calls for more R&D and investment in these sectors. For example, nano-sensors can be widely used in these sectors. While nanodevices can be used for tracking and recording purposes, 'Smart' packaging can enable real time monitoring of food quality and enhance the shelf life of food products. Similarly, nano-fertilisers and nano-insecticides are expected to

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open up possibilities that would enable appropriate use and safer handling of these chemicals. But this convergence also raises many issues relating to regulation, particularly in health, safety and environmental impacts. While the regulatory regime is evolving rapid advances in technology result in availability of products for consumers use. Hence the question of labelling and informing consumers becomes important. In case of agriculture and food, producers, distributors and consumers need to be made aware of the potential of technology and handling it safely.

In India nanotechnology is funded under Nano Mission that is administered by the Department of Science and Technology while other departments and ministries are also funding research in nanotechnology. In case of agriculture and food some of the initiatives have focused on impacts on nanotechnology and understanding them in the Indian context. For example a Brainstorming Workshop on "Prospects of Nanotechnology in Agri Value Chain" was organised at the National Academy of Agricultural Research Management (NAARM), Hyderabad during February 2011. The Workshop was attended by nearly 75 participants from the National Agricultural Research System, NanoMission Programme of GOI, leading universities, private sector companies and farmers. It was organised with the primary objective to explore the potential of applications of emerging nanoscience and nanotechnology in the agricultural value chain. It was in the plenary session of this workshop where Dr. Ravi Srinivas, Managing Editor, *ABDR* talked about the special issue of Asian Biotechnology and Development Review addressing agricultural applications of nanotechnology in India.

This special issue on 'Nanotechnology and Nanobiotechnology in Agriculture and Food' brings forth eight articles (research papers; reviews; country report; critique and book review) which highlight various facets of nanotechnology in R&D innovation in the agricultural production-consumption system in India and other developing countries. The first three articles focus on issues that concern most researchers engaged in applications of nanotechnology in agriculture- water, health and food packaging. The remaining articles provide a perspective on responsible management of R&D in agricultural nanotechnology and nanotechnology R&D in public sector in India. Thus the issue covers both the technical issues and the broader issues related to nanotechnology in food and agriculture.

Agriculture sector is a major consumer of water and issues of water security are strongly linked to food and nutrition security. In recent years, developments in nanotechnology are beginning to be applied in the water sector, particularly for water purification for drinking purposes. The first article by Kalpana Sastry and co-authors (*Prospects of Nanotechnology for Enhancing Water and Nutrition Security*) discusses the trends in nanotechnology impacting water resources augmentation, conservation and use. The four determinants of water security, mainly water filtration; waste water treatment and remediation; monitoring water quality and soil moisture; and irrigation systems were identified. These determinants of water security have significant implications for food and nutrition security, and can be impacted directly by nanotechnology. They present the application of a framework and a model for assessment of the potential of nanotechnology applications in agriculture developed through empirical research studies, and R& D indicators like literature and patent data to organise and map nanoresearch areas to the water security determinants. Emerging nanotechnologies can be focused on these key determinants to catalyse the research and develop a sustainable water security system. The study indicated that nanotechnology has a large canvas and great potential to address water security as compared to conventional methods and technologies. The initial success of providing nanotechnology-based solutions for access to safe potable drinking water needs to harness into viable business models to provide non-toxic water for agricultural sector.

Despite the high promise of nanotechnology, it is essential that understanding, integrating and deploying new advancements in nanotechnology in the agricultural value chain be made after understanding the various health, environmental and societal and implications. The agriculture sector is particularly vulnerable ecologically, and supports the livelihood and sustenance of diverse stakeholders. The article by Shashi Bhushan and Gautam Kaul (*Health Hazards Associated with Engineered Nanomaterials)* effectively raises genuine concerns of safety and possible toxicological impacts of engineered nanomaterials (ENPs). Contending that these materials possess immense potential for applications across several sectors including agriculture and food, the authors rightfully point the broader impacts on society if these materials are not handled safely. The article emphasises the need for research to generate data on safety and nanotoxicological evaluation of potential or putative hazards to human health, in particular, and the environment at large. Since these are relatively new particles, it requires carefully designed environmental, human health, animal health and safety research, meaningful and an open discussion of broader societal impacts, and urgent toxicological oversight action especially in the context of agriculture and food sector.

Effective food packaging has significant implications for food security and quality as well as for consumer convenience. Venkateshwarlu and Nagalakshmi in their article *(Developments in Bionanocomposite Films: Prospects for Eco-friendly and Smart Food Packaging*) describe the need to develop biodegradable films from natural polymers such as cellulose, starch, gelatin and chitosan in lieu of synthetic petrochemical based packaging materials which are not environment friendly. Nanotechnology interventions leading to the development of nanocomposite films incorporated with nano materials in the form of either nano-fibers or nano-whiskers provide the much needed improvements in biopolymer packaging films. Recent advances in the development of food packaging films have allowed integrating bioactive molecules (active packaging) to extend the shelf-life of food by incorporating biosensors (smart packaging) that recognise spoilage of food.

The next two articles discuss the R&D climate in India for nanotechnology and nanobiotechnology and the need for responsible innovation through nanotechnology. Research in nanoscience and nanotechnology is in early stages and centered in public systems to a large extent. The article '*Overview of Nanobiotechnology Public R&D System in India*' by Amit Kumar and Pranav Desai describes the influence of nanotechnology on agricultural biotechnology, including crop, animal and environment biotechnology. The wide array of nanobiotechnological interventions possible in these fields has greater significance for countries like India. In this context, the pioneering role played by the government bodies/public R&D in promoting this stream of technology is commendable. The authors emphasise the need to invest in risk assessment protocols simultaneously with investments for R&D in nanobiotechnology.

The critical analysis by Poonam Pandey in her article '*Moving Forward Responsibly: From Agribiotechnology to Agrinanotechnology in India*' articulates the much discussed agribiotechnology debates in India over the last decade which have changed the interrelationships between science and society. Taking cue from these debates, this article stresses on the need to assimilate them while prospecting for new nanotechnological interventions in agriculture, keeping in mind the need for responsible governance regulation. In this process, the article opens up the parallel international debate on 'Responsible Innovation' (RI) in the context of emerging technologies, for scrutiny in the Indian context.

As part of understanding the debates, the special issue has an interesting forum article which discusses 19 case studies where agricultural biotechnologies were used to serve the needs of smallholders in developing countries. Based on a study commisioned by FAO, James Dargie and co-*authors (Biotechnology Experiences in Crops, Livestock and Fish for Smallholders in Developing Countries)* discuss ten general and interrelated lessons which can be used to inform and assist policy-makers when deciding on potential interventions involving biotechnologies for smallholders in developing countries. Issues of absolute commitment, participation of all actors (policy makers, donors, and farmers), flexible approach, better planning and monitoring emerged as areas to focus on for improving governance. The next article, is a a report about the conference on Africa-India Cooperation for Science, Technology and Innovation held in New Delhi on 22 October 2013. The conference was organised by RIS in collaboration with The Energy and Resource Institute (TERI), The New Partnership for Africa's Development (NEPAD) and Michigan State University (MSU). The current trend of having a multi dimensional perspective on R&D is also evident from this report with participation from diversified fields including academia, business and industry circles and representatives from the Indian and African Governments.

Finally, a brief review by Amit Kumar about recent book *Nanotechnology in the Agri-Food Sector: Implications for the Future* brings forth the various facets presented in this voluminous book. This edited book by Lynn J. Frewer, Willem Norde, Arnout Fischer, and Frans Kampers details the integration of nanotechnology into the agri-food sector along with the analysis of associated risk, public engagement and ethical considerations involved.

It is hoped that this Special Issue will kindle the interests of readers on nanotechnology and nanobiotechnology in food and agriculture and will enable them to explore further the applications and implications of nanotechnology and nanobiotechnology. We would like to thank the contributors for their valuable contributions. Your comments and suggestions are welcomed.

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Asian Biotechnology and Development Review
Vol. 15 No.3, pp 7-35

Prospects of Nanotechnology for Enhancing Water and Nutrition Security

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Abstract: In India and other developing countries water security and food and nutrition security are intricately connected. Developments in nanotechnology can have significant implications for water resources augmentation, conservation and use. A framework for assessment of the potential of nanotechnology applications for enhancing water security is developed. Water filtration, waste water treatment and remediation, monitoring water quality and soil moisture and irrigation systems are identified as key determinants of water security that have significant implications for food and nutrition security, which can be impacted by developments in nanotechnology. Using literature and patent data, a model to organise and map nanoresearch areas to the water security determinants is developed. The model is based on a specially designed database, which allows identification and prioritisation of nanotechnologies to enhance water security. The potential for commercialisation of some promising nanotechnologies is also assessed.

Key words: Water management, nanomaterials, nanotechnology mapping, patent analysis

Introduction

Water security and food and nutrition security are intricately connected. Any shortage in water supplies for drinking or agriculture negatively impacts health, agricultural production, and, therefore, food and nutrition security of nations. Fresh water is less than 3 per cent of the total world's natural supply, 97 per cent being salt water. Two-thirds of available fresh water is frozen in glaciers, ice caps and icebergs. Only 1 per cent of the total natural supply is available for direct use as fresh water. This supply is shared among multiple uses: human and animal consumption, agriculture,

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urban uses, industry and provision of environmental services. Globally, agriculture consumes the largest share of available fresh water resources, about 70 per cent. In developing countries like India the share of agricultural water is over 90 per cent.

The total available fresh water supplies will remain essentially fixed, while the global population is expected to increase to 9 billion by 2050 from the present 7 billion. With increasing urbanisation, industrialisation, and environmental demands for water, agriculture will be the first to lose water to competing sectors. A recent assessment by the United Nations (UNDP 2007) indicates that water scarcity, and not lack of arable land, is more likely to limit future food production. By 2050, even after improving water management in irrigated agriculture and upgrading of rainfed agriculture, water supplies are expected to fall short by about 3300 km^3, or about 27 per cent of global water demand of 12400 km^3 (Hanjra and Qureshi 2010). In the developing countries, where most of the population increases will take place, the water shortages and impacts on food security will be significantly higher. Further, as water is also the primary medium through which the climate change effects will be felt by the agriculture sector, its expected impacts in the form of water supply shortages and uncertainties will only compound the difficulties in ensuring adequate future water supplies for agriculture.

Water planners are, therefore, examining a number of alternatives to augment the available fresh water supplies. These include adopting more efficient water conservation methods and technologies, better policies and management of water resources in agriculture and other sectors, and augmenting available freshwater supplies with water from alternative sources. While the first two are widely prevalent for improving available fresh water supplies, supplementing the existing supplies from alternative sources is increasingly emerging as a viable option for ensuring future food security (OECD 2009). Alternative sources of producing fresh water include waste water filtration, purification, desalination, recycling and reuse, etc. Though many of these technologies have been known for some time, they have not had a significant impact in augmenting water resources on a large scale. Among the reasons for this are their unfavourable economics, large requirements of materials and physical infrastructure, public policies, and risk perceptions (Brame *et al.* 2011). There is a need for new and more effective technologies to significantly enhance the available water resources for agriculture to meet the future demands. The report of the World Water Forum (2012) forecasts that by 2025 water management can be significantly affected by advances in science and technology in non-water sectors which will have profound impacts on the water sector. Nanotechnology is among the most prominent emerging technologies of the 21st century that is expected to dominate science and technology development over the next several decades.

The objective of this article is to assess the innovation landscape of nanotechnology for augmenting water resources for food and nutrition security and its broader implications for technology commercialisation and governance. The potential of nanotechnology has been widely recognised and it is being applied to many areas (e.g. medicine, energy, electronics, materials, etc.; Meridian Institute, 2005). Interest in nanotechnology applications in the agriculture, food and water sectors is relatively recent (Savage *et al.* 2009; Sastry *et al.* 2010a,b and 2011a,b; Gruere 2012; Brame *et al.* 2011; Xiaolei *et al.* 2013). The technology has the potential to affect water availability by both *enhancing* the traditional water technologies and *introducing radically new* technologies (Savage *et al.* 2009; OECD 2010; OECD 2012). A UN Survey on potential applications of nanotechnology in developing countries identified agricultural productivity enhancement and water treatment as the second and third priority areas respectively for attaining the Millennium Development Goals (Salamanca-Buentello *et al.* 2005).

Prospective Landscape of Nanotechnology

Nanotechnology has been defined as the ‘‘understanding and control of matter at dimensions of roughly 1-100 nanometers (10^{-9}m), where unique phenomena enable novel applications’’ (Roco 2003). Nanotechnologies are technologies which either incorporate or employ nanomaterials or involve processes performed at the nanoscale. At this scale, the physical, chemical and biological properties of materials differ fundamentally from the properties of individual atoms and molecules or bulk matter. These changes result in unique mechanical, physical, chemical, electronic, photonic and magnetic properties of nano scale materials. The ability to manipulate matter at the nano scale can lead to improved understanding of biological, physical and chemical processes and to the creation of improved materials, structures, devices and systems that exploit these new properties. Because of this general purpose enabling nature, nanotechnology has the potential to impact all sectors of human development. For this reason, developments in this field have been fostered by significant and sustained investments in research and development, by both public and private sectors in nations across the world. As the field transforms from a largely scientific to a commercial undertaking, it is also becoming increasingly competitive. Regions (for example, Europe), nations (the USA, Sweden, among most developed countries; China, Brazil, India among developing countries), institutions, companies and even individuals (Nanowerk 2014) are developing strategies and launching initiatives to invest in technology capacities and gain a competitive position in the field to reap its expected benefits. Public and private global investments in nanotechnology research and development in 2010 totalled approximately $17.8 billion, with private investments accounting for more than half ($9.6 billion) of the funding (Sargent 2012).

Despite such major investments, assessing and forecasting applications of an emerging technology like nanotechnology in any major development sector like water can be uncertain and difficult. This is because not much historical data of applications and impacts is available as the technologies are relatively nascent. Though several nanotechnology products are becoming increasingly available in the market, large scale commercial applications of nanotechnology, that can impact development related activities are not expected in the near future. In such situations, use of patent analysis and bibliometrics can provide useful data on emerging technology trends and potential applications (Hullmann and Meyer 2003; Daim *et al.* 2006; Kostoff *et al.* 2007; Sastry *et al.* 2010b). While journal publications track developments in basic research, patents indicate the potential for commercial applications. Patent documents are also well structured to provide standardised information about citation, issue date, technology field classification, inventors, institutions and their locations, etc. Such structured documentation makes them suitable for assessing future technology developments in various areas. Bibliometric data of journal publications on the other hand are less precisely structured but amenable to formal key word searches and more intensive text mining approaches for technology assessment (Sastry *et al.* 2011a)

A key differentiator of innovation in nanotechnology is that it involves a highly diverse, distributed and complex value chain. The nanotechnology value chain includes a diversity of players in both public and private sectors with different commercial and strategic interests: large and small companies, public and private research organisations, investors, equipment suppliers, intermediaries and end users, regulators, and other stakeholders (Roco *et al.* 2010). The growth in number of patents and publications worldwide in the nanotechnology domain has been explosive since 2000 - global annual growth rate of over 20 per cent for scientific literature (Science Citation Index papers) and nearly 35 per cent for patents (Roco *et al.* 2010). Between 1990 and 2008, about 52,100 scientific articles were published and there were about 45,050 patents. The ratio of corporate nanotechnology patents to corporate nanotechnology publications increased noticeably from about 0.23 in 1999 to over 1.2 in 2008. This changing ratio in favour of patents indicates a shift in corporate interest from discovery to potential commercial applications (Chen and Roco 2009), while ensuring control over the intellectual property in anticipation of large markets in future. The value of products incorporating nanotechnology was about US $ 200 billion in 2008. With the market doubling every three years, it is expected to cross the 2000 forecast for 2015 of US$ 1.0 trillion (Roco *et al.* 2010). Most patents in nanotechnology are owned by large companies. In recent years, small and medium-sized enterprises (SMEs) have also increased their patent filings, leading to multiple upstream core technology patents. The diversity in ownership of patents, and of potential applications because of its enabling nature, is leading to the emergence of a dense web of overlapping Intellectual Property Rights (IPRs) or ‘Patent thickets’ in nanotechnology. The thickets create new barriers for commercialising nanotechnologies, as organisations have to deal with overlapping IPRs. New forms of organisation and business models are emerging in this domain with new paradigms and capabilities that can be more disruptive than other revolutionary technologies of the recent past, like electronics and biotechnology (Mantovani *et al.* 2009).

In the water sector, the complex value chain of nanotechnology and the patent thickets present significant challenges for technology development and transfer. The challenges range from prioritising investments in nanotechnology research and development to building capacities and fostering innovation, balancing cooperation and competition to ensure access to the new technologies by navigating through the patent thickets, addressing the ethical and legal implications, and assessing the long term environmental and social impacts of the technologies. These raise important questions for public policy and governance of nanotechnologies for water at national and global levels.

This article develops a framework for assessing the innovation landscape of nanotechnologies for water resources augmentation for agriculture with the purpose of leading to a roadmap for their future development and governance in this important area. The article is organised in three stages:

- Designing a framework to map the trends in nanotechnology research and development to specific thematic areas relevant to augmenting water resources. Published literature and patents data are used to identify key areas, and track and map the technology trends.
- Assessing the diffusion of few nanotechnologies and their commercialisation in the water sector, including their environmental and social impacts.
- Developing a focussed strategy for future investments in nanotechnology research in water resource augmentation for food and nutrition security.

Framework for Mapping Trends in Nanotechnology to Water Resource Augmentation

The framework for assessing nanotechnology applications to enhance water resources for agriculture is developed based on:

- identification of key areas where nanotechnology has potential for augmenting water resources, from a literature assessment, and
- mapping the nanotechnology research areas to the water resources augmentation areas, using patents and literature databases

Nanotechnology Applications for Water Resource Augmentation

Developments in nanotechnology can be broadly classified into three categories, in order of their chronology: nanomaterials (nanoparticles, quantum dots, dendrimers, nanotubes, etc), nanodevices (e.g.. nanosensors), and nanosystems (interacting materials, structures, components and devices that process materials, energy or information). The categories overlap as the technology evolves to develop new materials, devices and structures for application in different areas. For water resources augmentation, two broad application areas are possible: (i) improving efficiencies of operations in both water systems and agricultural production systems to make additional supplies available from existing sources; and (ii) making new resources available from alternate sources.

In the first area of improving water efficiencies, all three categories of nanotechnologies – nanomaterials, nanosensors and nanosystems – have been in use. Different types of nanomaterials have been derived from nanoparticles obtained from a variety of sources including natural sources, carbon nanotubes, nano-cantilevers, and nanosurfaces. Wireless nanosensor networks are already being used in agriculture for intensive sensing of environmental conditions to control the automated application of water, as well as fertilisers and pesticides (US Department of Agriculture 2003; Rickman 2003). The sensors detect soil moisture stress levels to automatically adjust irrigation amounts and timings in the field in real time, leading to more efficient water use, better crop yields and lower costs. Nanosensors have also been fitted to combine harvesters to measure the amount and moisture levels of grains being harvested on different parts of a field, to enable computers guide decisions on timing and application of water inputs. Among nanosystems, electronic chips with nano-scale features have been combined into wireless networks of 'motes' (miniature, self-contained, battery-powered computers with radio links that can self-organise into networks and communicate with each other to exchange data) that can be used on the farm for irrigation management, frost detection and warning, pesticide application, harvest timing, bio-remediation and containment, and water quality measurement and control (Galcon 2009). Networked sensors scattered on fields can also provide detailed data on crop and soil water content and relay that information to the farmer. As nanotechnology developments lead to better and cheaper materials and sensors, this technology can be more widely applied to save water, reduce water pollution and enhance crop productivities.

The second area of nanotechnology applications in water, namely augmenting water resources from alternate sources, deals with the use of the technologies for wastewater purification and desalination. Use of treated or untreated wastewater to irrigate crops is common in developing country agriculture among peri-urban farmers located near streams carrying municipal or industrial wastes. Much of the wastewater use is informal and unplanned. Though the farmers earn good profits from nearby urban markets, the wastewater irrigation leads to soil and water pollution and health risks for both farming communities and consumers (Wichelns and Drechsel 2011). Such use of untreated or partially treated wastewater for irrigation is only likely to increase substantially in future as higher-quality water supplies are shifted from agriculture to other competing uses. The cost of comprehensive wastewater treatment by traditional means is prohibitive because of its large infrastructure requirements, even as the infrastructure ages and generation of wastewater increases with population growth.

Since many traditional water treatment technologies (membrane filtration, biofouling prevention of scaling, desalination, etc.) depend on nanoscale processes, and as many biotic and abiotic impurities in water are in the nanoscale range, nanotechnology can potentially contribute to new and economical solutions in this domain (Savage *et al.* 2009). Research on nanotechnology-enabled water treatment has focused broadly on three areas (Brame *et al.* 2011):

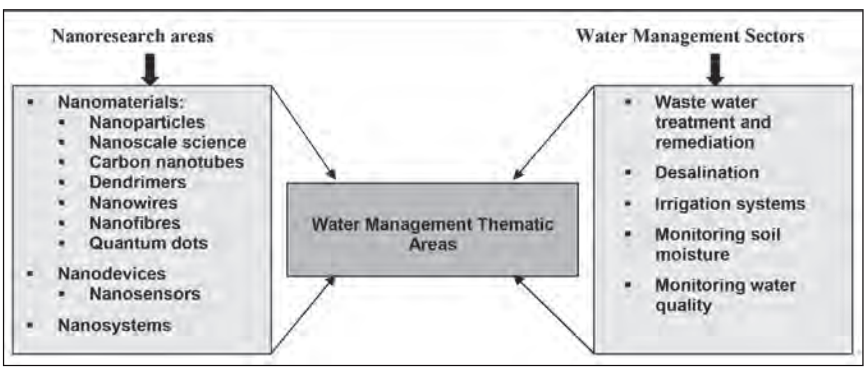
- adsorptive removal of pollutants which relies on high absorptive properties of nanomaterials arising from their large surface to volume ratio (eg. magnetic iron oxide nanoparticles for removal of arsenic);
- catalytic degradation and disinfection which relies on enhanced catalytic properties of some nanomaterials for oxidative or reductive degradation of contaminants, or disinfection (e.g. Titanium dioxide nanoparticles composites for treatment of pesticides and bacterial and viral inactivation); and
- membrane filtration and desalination in which multiple nanomaterials (adsorptive, catalytic and antimicrobial materials like TiO_2 and Silver nanoparticles) are incorporated into water treatment membranes for multiple water treatment functions and also for protecting the membranes themselves from fouling.

The state-of-the art of technology development across the above areas is uneven, and membrane filtration with nanomaterials appears to be relatively more advanced. Many of the applications are at lab scale, some (e.g., iron oxide for arsenic removal from groundwater) are being pilot tested in fields, and some are at domestic scale commercial appliances level (e.g., water purification devices for homes and small scale use). The applications are driven by reduced costs, improved ability to selectively remove contaminants, durability, and size of devices. Future generations of nano-based water treatment devices are expected to be more complex, flexible, and effective and will be designed to exploit new properties of nanoscale materials. Advances in nanotechnology based water treatment, therefore, may be of significant interest to both developed and developing country agriculture, and to the public and private sectors.

Mapping Nanotechnologies to Water Resources Augmentation

Based on technology roadmapping and database management concepts, a framework was developed earlier in an ongoing project on ‘‘Assessing Interrelationships between Developments in Nanotechnology and Agriculture’’ (NAARM 2010; Sastry *et al.* 2010a,b and 2011a,b). In this framework, the bibliographic and patents data are assembled in independent relational databases in MS Access and the information relevant to the thematic areas across the agricultural value chain is drawn using a database query process. This framework is adopted to map the nanoresearch areas to the water management thematic areas (Figure 1).

Figure 1: Framework for Integrating Nanoresearch Areas and Water Management



Source: Based on data collected from various sources by the authors.

A five-step approach was followed: (i) identification of nanoresearch based on a general survey (literature data) of nanoresearch themes and water management thematic areas (Table 1); (ii) relating nanoresearch areas (Figure 2) with the agri-food thematic areas through a filter of the water management areas; (iii) designing two MS access databases for R&D indicators (bibliographic sources-61 and patents-422), to query, analyze and map the technology trends that connect both nanoresearch and water management themes; (iv) designing a bibliographic search strategy to populate the bibliographic database; and (v) designing patent search strategy to build the patents database (Sastry *et al.* 2010a).

The framework and database allow for mining information in specific areas of application of nanotechnology in water management, and for assessing their environmental, ethical, legal and societal implications. The distribution of R&D indicators for various nanoresearch areas (nanoparticles, nanotubes, nanofibres, etc.) with applications (or potential for applications) in water management for agriculture is given in Figure 3. The converses, namely the distribution of R&D indicators for water management that involve applications of nanotechnology, are shown in Figure 4.

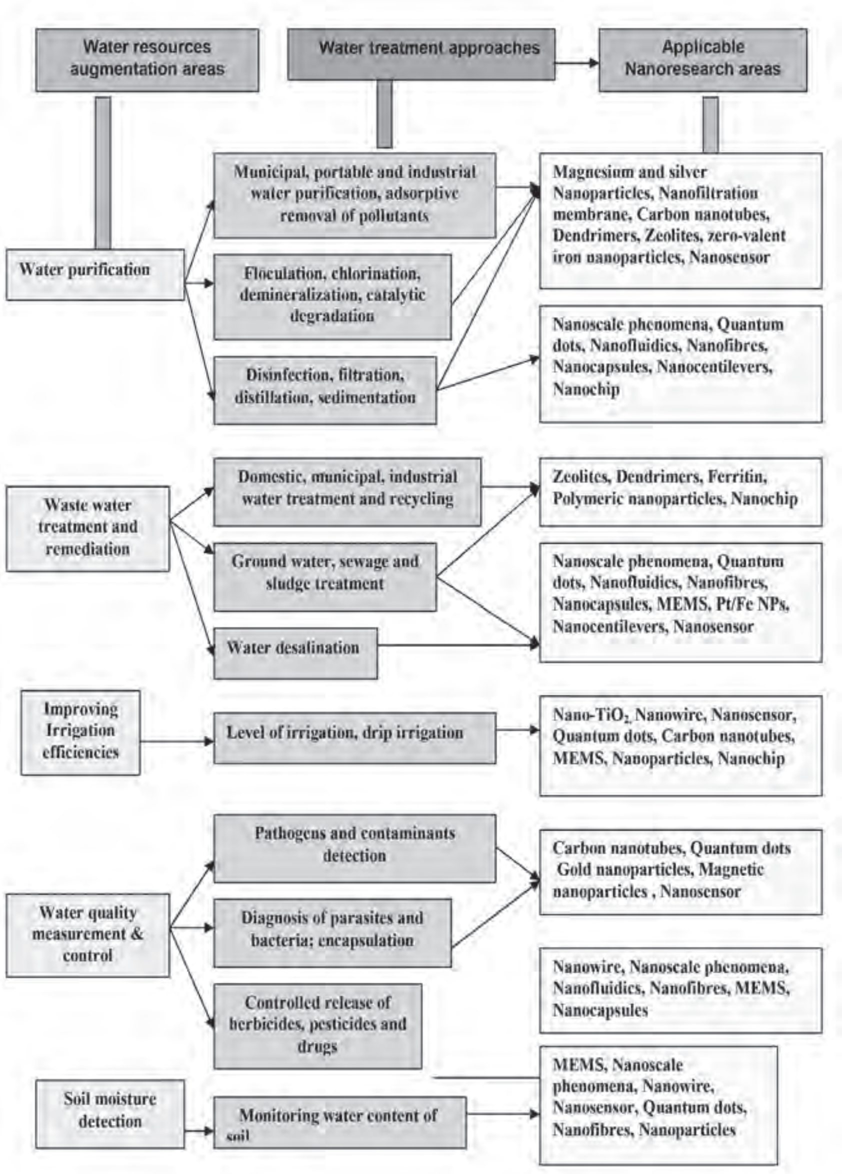
Patent Data Analysis

The trends in patents were studied on the following parameters:

Patent Timeline Analysis Using Reference Dates

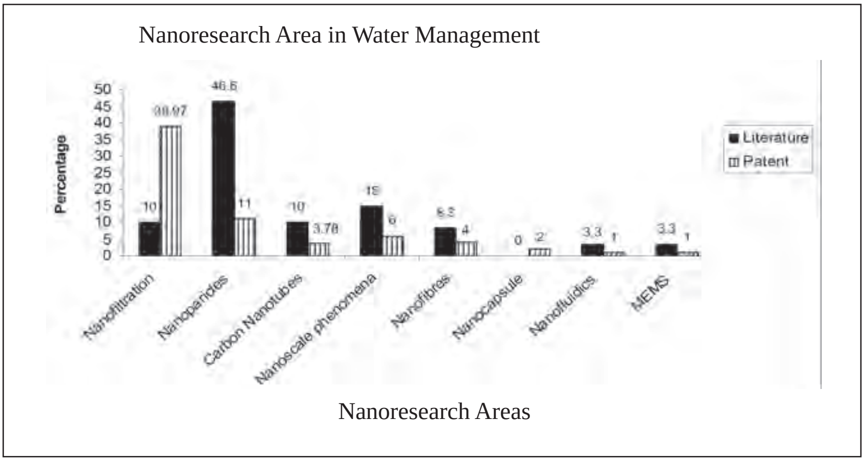
In the present study, the patent data was collected based on a specially designed strategy. Patents related to "Nanotechnology and water management" were searched, collected and analysed from three resources, viz. freely available databases of international/national patent offices (USPTO, EPO, iPAIRS and WIPO); non-charge providers (Google patents, Free patents Online) and charge provider (Questel). A set of subject specific keywords and standardised search strings was identified by domain experts and used to perform full text search of patents (patent titles, abstract, claim and description). A set of 422 relevant patents related to nanotechnology and water management were retrieved after filtering out the unrelated patents. Unit of analysis and representation in text mining of patents include technology fields, nanoresearch areas and timelines.

Figure 2: Knowledge Mapping Framework for Integrating Determinants of Water Resources Augmentation Areas with Nanoresearch Area



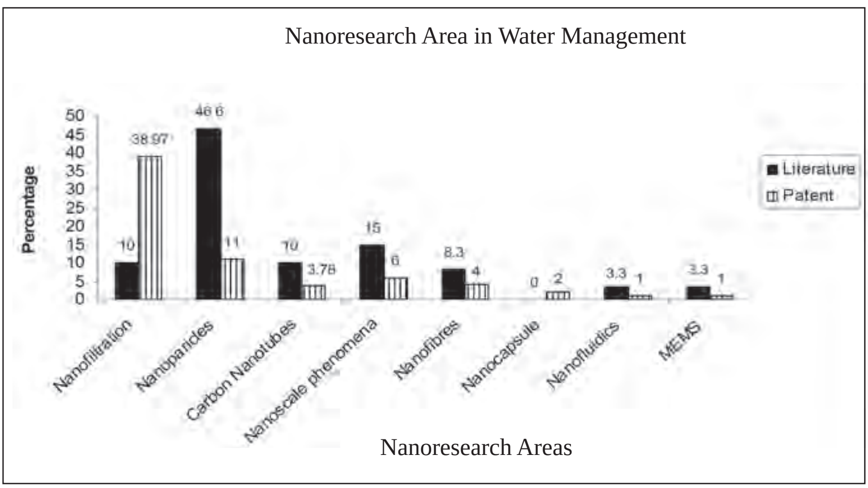
Source: Based on data collected from various sources by the authors.

Figure 3: Distribution of R&D Indicators of Nanoresearch



Source: Based on literature (n=60) and patents (n=422) collected from various resources by the authors.

Figure 4: Distribution of R&D Indicators of Water Management viv-a-vis Applications in Various Sectors of Water Management



Source: Based on literature (n=60) and patents (n=422) collected from various resources by the authors.

Table 1: Tabulation of Nanotechnology Based Research for Water Management in Agriculture

Sector of Water Management	Nanomaterials and Technologies
Water filtration	a) Membranes: Used in microfiltration, reverse osmosis; all suspended solids, impurities and particles are removed by sedimentation, disinfection aeration and filtration (OECD 2011). b) Nanoparticles enabled membranes: Used in removing water hardness (calcium and magnesium) (OECD 2011). Magnetic nanoparticles used to remove salts and metals and also encourage the decomposition of organic materials (Roh 2006) Magnesia (MgO) and magnesium (Mg) nanoparticles are very effective biocides against bacteria and bacterial spores (Stoimenov 2002). Silver and silver compounds have been used as antimicrobial compounds for coliform in waste water (Jain and Pradeep2005). Zinc oxide nanoparticles have been used to remove arsenic from water (Kalaugher 2004). c) Nanofiltration: It removes cations, natural organic matters, biological contaminant Organic pollutants, nitrates and arsenic from ground water and surface water (Vander and Vandercasteele 2003). d) Carbon nanotubes: Cylindrical membranes of CNT filters help in removal of bacterial pathogens from contaminated water (Srivastava *et al.* 2004). e) Chemically reactive nanofiltration membrane: It has high water flux, high retention of divalent cations, sorption of metal ions from water (Stanton *et al.* 2003). f) Dendrimers: It is used in first step of water treatment in order to bind contaminants, and then a second step of filtration would produce pure water from which contaminants have been removed or modified (OECD 2011). g) Zeolites: Used in catalysis, separation and ion exchange. The capacity for ion exchange is exploited an a major way in water softening ,where alkali metals such as sodium or potassium prefer to exchange out of the zeolite, being replaced by the "hard" calcium and magnesium ions from water. (Tavolaro *et al.* 2007). h) Macromolecular nanotechnologies for polymer enhanced filtration: Used in removal of pesticides, organic contaminants and metal ions from aqueous solution. i) Zero-valent iron particles and derivatives: Used in neutralising organic solvents, fertilisers, pesticides and metal contaminants (Tratnyek 2006) .

Table 1 continued...

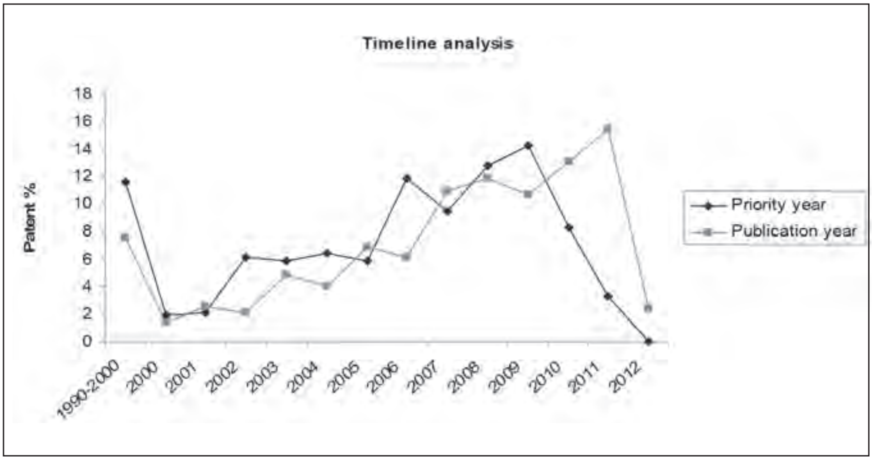
Table 1 continued...

Waste water treatment and remediation	a) *Zeolites:* These have the ability to remediate water containing cationic species, such as ammonium and heavy metals, as well as chemicals, such as Cs and Sr. These radioactive species are found in nuclear plant waste water and polluted ground water (Bowman 2002). b) *Ferritin:* These remediate toxic metals and possibly chlorocarbons in the presence of visible light or solar radiation (Moretz 2004) and also help in photo reduction of contaminants (Kim 2002). c) *Dendrimers:* These nanoparticles are mixed with contaminated waste water, where they subsequently bind to metal ions present and through ultra filtration. These ion can be detached and removed while dendrimers can be reused. So dendrimers acts as chelating agents for metal ions (Diallo 2005). d) *Polymeric particles:* These offer a potential replacement for traditional surfactants commonly used to enhance the remediation of hydrophobic organic conataminants using pump-and-treat system. Contaminants falling into this category often sorb strongly from nonaquous phase liquid (Yeom *et at.* 1996). e) *Self assembling monolayer on mesoporous support (SAMMS):* It allows the removal of mercury and potentially other metals, such as cadmium, silver and molybdenum from waste water (SAMMS technical summary 2005). f) *Bimetallic Pt/Fe nanoparticles:* Fe serving as the reductant for water to generate hydrogen while the second metal acts as catalyst (Schrick *et al.* 2002). g) *Titanium dioxide(TiO_2):* It acts as photo catalyst and remediate fuel-contaminated groundwater containing benzene, toluene, ethylbenzene and xylene compounds (NATO 1998).
Monitoring soil moisture	*Nanomaterial based biosensors* MEMS sensor: MEMS sensors are composed of micromachined MEMS cantilever beams equipped with a water sensitive nano-polymer and an on-chip piezoresistive temperature sensor. The sensor is based on a shear stress principle in which the microsensor chip combines a proprietary polymer sensing element and Wheat stone Bridge piezoresistor circuit to deliver two DC output voltages that are linearly proportional to moisture and temperature. These embedded wireless MEMS sensor used for soil temperature and moisture measurements (Jackson *et al.* 2008).
Monitoring Water quality and pathogens detection	*Nano-based electrode with fluidics system and nanomaterials based biosensor* (carbon nanotubes, gold nanoparticles, magnetic nanoparticles, quantum dots metal oxides and polymers) incorporating a biological sensing element, used for the production of concentration-based proportional signals when pathogens or contaminants are present (OECD 2011) .
Irrigation	Nano TiO_2: It acts as photocatalyst which decrease the microbiological load in irrigation water and also supported in concrete mortar that could be used as a channel's lining for irrigation (Hoz *et al.* 2009).

Source: Based on literature (n=60) collected from various resources by the authors.

Reference date in patent documents reflects timing of invention, process and strategy of the applicant. In the present study, two indicators, namely priority year and publication year, were used to gauge trends in inventive activities over a span of years. It is known that priority date/year is the first date of filing of patent application anywhere in the world and considered closest to the invention date while publication year reflects the time the information is disclosed to the public from statutory offices. Using priority date is most often recommended as it reflects the inventive performance of technologies, while publication year reflects the rate at which statutory officers are working on these technologies and, therefore, the time from which it forms full prior art for other patent applications worldwide (Sastry *et al.* 2011b). The quantum of patents on application of nanotechnology in water management (Figure 5) shows an exponential growth (priority year) during years 2001-09, which declined from 2010-11.The same trend was observed in publication year, though not coinciding with the priority year. This difference may be due to the fact that patent offices need to examine field applications in conjunction with relevant national laws and time taken for publication differs in each country.

Figure 5: Patent Timeline Analysis (n= 422)



Source: Based on patents set (n=422) collected from various resources by the authors.

Technology Trend: IPC Analysis

The patents in various subfields of the categories under IPC (IPC 2013) were distributed in 20 IPC classes (till sub class level or the third hierarchical level of classification) covering a number of sectors. It is well known that a patent application can be associated with more than one IPC class and one patent may occupy more than one subclass. IPC code analysis was restricted to the fourth hierarchical level of the classification that is 'group' level. It was found that maximum number of patent records was in IPC group C02F 001/44 which covers dialysis, osmosis or reverse osmosis for waste water treatment and resource recycle. The other prominent IPC codes, under which the data studied were classified, are listed in Table 2.

Table 2: Distribution of patents based on IPC* classification

IPC code	Major Technology	Patent (per cent)
C02F 001/44	Treatment of water by dialysis, osmosis or reverse osmosis	30.73
B01D 061/02	Reverse osmosis; Hyper filtration; Microfiltration	16.54
C02F 001/28	Sorption; Ion exchange	13.17
C02F 001/00	Treatment of waste water or sewage	12.05
C02F 009/00	Multistep treatment of waster water	10.40
B01D 061/00	Process of separation using semi-permeable membrane, eg. dialysis, osmosis or ultrafiltration	9.69
B01D 061/14	Ultra filtration; Microfiltration	9.21
C02F 001/42	Waste water treatment by ion exchange	7.09
B01D 065/00	Filtration using semi-permeable membrane	6.61
C02F 001/72	Treatment of waste water by oxidation	6.61

Note: *Total set of 422 patent records; Technology analysis by WIPO IPC version 2012.01.

Source: Analysis by Authors.

A detailed study of whole text patent documents with reference to the nanoresearch areas associated with the determinants of water security was also carried out. The maximum number of patents was found for the, nanoresearch area "Nanofiltration". These were found applicable in the areas of water treatment, desalinisation, irrigation, waste water treatment and purification. The other nanoresearch areas, nanoparticles, carbon nanotubes, nanoscale phenomena and processes, nanofibres, nanocapsules and nanofluidics were also analysed for their relevant applications in water management (Table 3).

Table 3: Classification of relevant patent set* into nanoresearch areas of water management

Nanoresearch Area	Water area	Patent (per cent)
Nanofiltration	Antimicrobial water treatment, desalinisation, irrigation, waste water treatment and purification	38.97
Nanoparticles	Waste water treatment, irrigation, degeneration of plastic mulching used in agricultural fields	11
Nanoscale phenomena and process	Irrigation, soil moisture detection	6
Carbon nanotubes	Nano-mulching, waste water treatment	4
Nanofibres	Waste water treatment, desalinisation and purification	4
Nanocapsule	Waste water treatment	2
Nanofluidics	Water filtration	1
MEMS	Purification of water, irrigation	1

Note: * Total set of 422 patent records; full patent document studied and per cent patent of each nanoresearch area analysed.
Source: Analysis by Authors.

Technology Flow Analysis

Patent citation analysis was done to understand diffusion of technologies in the water sector. Tools like estimation of patent value through backward citation (technology inflow) and forward citation (technology outflow) were used. A reference patent was selected from the set of 422 patent data on the basis of maximum number of citations and citation velocity (ratio of forward and backward citations). It is known that greater citation velocity (i.e. less backward citations and more forward citations) indicates that the technology is very novel and not an improvement over the existing technology, and has better prospects of gaining market value (Mohapatra 2008). On this basis, the patent record was then identified as the reference patent for water remediation/waste water treatment and citation maps were generated using forward and backward citations.

Citation Map Analysis of Nanotechnology in Waste Water Treatment and Remediation

The reference patent US7501065-B1 published in 2009 is based on *method of remediation of agricultural drainage water using nanofilter*. The technology involves removing sulphate and other impurities from water by compressed-phase precipitation using a membrane.

There were six backward citations and six forward citations. The technologies from backward citations focussed primarily on producing petroleum gas by treating waste water (US6663778B1), thermal power plant water treatment process (US4347704A), membrane distillation hybrid system for water treatment (US6365051B1), removal of alkaline and sulphate from sea water (US7093663B1), precipitation and separation of inorganic waste from aqueous solution (US5587088A) and method of making high density gypsum board and filter (US4327146A). Technology inflow to the base patent was through backward citations. The focus of these patents was found in techniques of precipitation and separation of organic waste from water bodies. These formed the prior art for novel technology for waste water treatment and remediation using nanofiltration membrane as indicated in reference patent US7501065.

Figure 6 shows the citation map for selected reference patent (US7501065-B1) in water remediation/waste water treatment sector. It can be observed that patent has been classified under major number of 'IPC-C02F' (treatment of waste water, sewage, sludge etc.) and 'IPC-B01D' (separation of solid from liquid). The six forward citations from this reference patent indicated a diversification of method of water treatment such as method to de-sulphate saline streams like sea water which can also produce de-ionised water and inorganic materials from such de-sulphated saline streams (US7789159B1). Some methods are also disclosed to treat water from hydrocarbon production facilities. The disclosed methods can also be used to partially de-salt, de-ionise, and de-oil to produce water (US7963338B1); precipitation of organic waste and recovery of fluid and saline water treatment (WO2011115636A1); removing boron from saline water using nanofiltration membrane (WO2013032528A1); waste water treatment by removing organic waste (WO2013033483A1); and precipitation of solid salt and organic solvent from water using membrane device (WO2013066662A1).

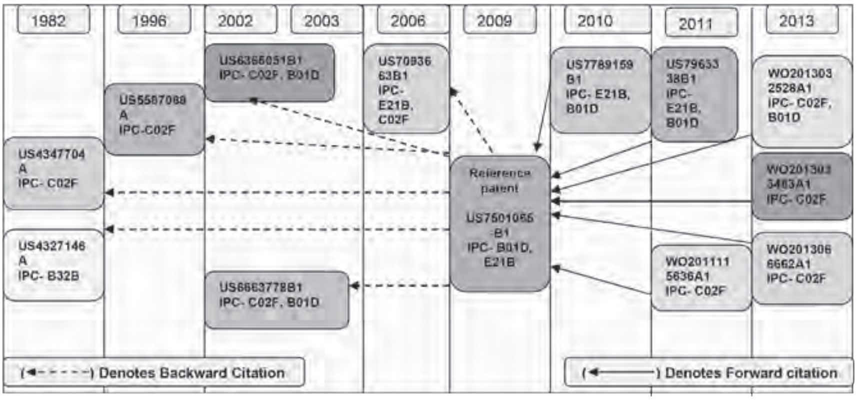
Technology flow analysis using backward and forward citations of reference patent has been summarised in Table 4.

Table 4: Technology Analysis using Backward and Forward Citations

Citation	Publication No.	Public-ation Year	Assignee	IPC	Technology
Cited Patents (Backward citations)	US6663778B1	2003	Bader Mansour S, US	B01D, C02F	Producing petroleum, gas by treating waste water
	US4347704A	1982	Hager and Elsasser GMBH, DE	C02F, F01K	Thermal power plant water treatment process
	US6365051B1	2002	Bader Mansour S, US	B01D, C02F	Membrane distillation hybrid system for water treatment
	US7093663B1	2006	Bader Mansour S, US	E21B, C02F, B01D	Removal of alkaline and sulphate from sea water
	US5587088A	1996	Bader Mansour S, US	C02F	Precipitation and separation of inorganic species from aqueous solutions
	US4327146A	1982	Nat Gypsum Co.	B32B, C04B	Method of making high density gypsum board and filter
Reference Patent	US7501065-B1	2009	Bader Mansour S, US	B01D, E21B	Remediation of agricultural drainage water using nanofilter
Citing Patents (Forward citations)	US7789159B1	2010	Bader Mansour S, US	E21B, B01D	Method to de-sulphate saline streams
	US7963338B1	2011	Bader Mansour S, US	E21B, B01D	Method of water remediation
	WO2011115636A1	2011	Gen Electric US	C02F	Saline water treatment
	WO2013032528A1	2013	Saline Water Desalination Research Institute, US, ABD Ellatif Abou Eleftouh Zaki, EG	C02F, B01D	Method of removing boron from saline water using nanofiltration membrane
	WO2013033483A1	2013	Gen Electric US	C02F, B01D	Method of waste water treatment
	WO2013066662A1	2013	Gen Electric US	C02F, B01D	Water desalination

Source: Based on analysis by the authors.

Figure 6:Technology Diffusion Process for Patent No. US7501065 in Waste Water Treatment Sector



Note: *Each box indicates: (i) patent application number/publication number with its status and (ii) IPC codes.

Source: Based on analysis by the authors.

Issues of Nanotechnology in Water Security and Its Management in Developing Countries

Among the emerging economies, China continues to increase its investment and promotion of scientific and technological innovation for water treatment, including nanotechnology solutions. In 2008, for example, researchers at the Research Centre for Eco-Environmental Sciences of the State Key Laboratory of Environmental Chemistry and Ecotoxicology, Chinese Academy of Sciences, have developed novel low-cost magnetic sorbent material for the removal of heavy metal ions from water by coating iron oxide magnetic nanoparticles (magnetite) with humic acid (HA). The coating has greatly enhanced the stability of the material and the heavy metal removal efficiency of the nanoparticles (OECD 2011). Israel is another important source of research and development in nanotechnologies, with 81 companies participating within Israel. In addition to initiatives such as the Israel National Nanotechnology Initiative (INNI), the Israeli government is investing over to USD 8 million for nanotech related equipment purchases and for advanced research projects in water treatment using nanotechnology (Ben-Artzi 2007). South Africa initiated a project using nanofiltration membranes to provide clean drinking water to rural communities. All of these indicate that developing countries are investing

Table 5: Tabulation of Examples of Point-of-Use Water Treatment Products based on Nanotechnology

Product	Company/ Institute	Technology(ies)	Cost	Applications	Reference
Puritech™	ARCI Hyderabad & SBP Aquatech Pvt. Ltd.	• Nanosilver coated ceramic filter	Price of candle- INR 75	• Remove turbidity, • Disinfected from bacteria.	ANF 2007. Sundararajan 2009. http://www.arci.res.in/latest-news-cnm.html
Tata Swach® Nanotech Water Purifier	Tata Chemicals, Tata Consultancy Services (TCS) & Titan Industries	• Filter having silver nano particles infused in rice husk ash. • The key component of the Tata Swach® water purifier is its cartridge, the TATA Swach® Bulb™.	INR 499; 799; 999	• Purify water from bacterial and other microbes contamination.	www.tatachemicals.com/products/tataswach.htm
Aquaguard Total™	Eureka Forbes Ltd. & IIT Chennai	• Use of silver/gold nanoparticles in water filter.	INR 9590	• Purifying water containing pesticides like chloropyrifos and malathion.	Pradeep *et al.* 2007. http://www.thehindu.com/news/cities/chennai/iitm-develops-lowcost-nano-water-purifier/article4446899.ece

Source: Based on data collected from various sources by the authors.

in applying nanofiltration technology to meet their needs of their citizens (Hillie *et al.* 2006). Brazil has also developed a cheap optical sensor incorporating nano assembled films to evaluate the acidity of natural water supplies (OECD 2011).

Nanotechnology Research and Development in Water Sector in India

In India, Nanotechnology is predominantly at the laboratory stage. However, some systems for water purification are at the development stage and some others have reached the market. Nano silver based products have been introduced in point-of-use water treatment systems which are given below:

- *Incorporation of nano silver in traditional candle filters for disinfection*: The coating technology has been developed at The International Advance Research (ARCI, DST), Hyderabad. About 100 such nanosilver coated candles have been field tested over an eight months period with both pond water and locally treated water. The technology has been transferred to SBP Aquatech Pvt. Ltd. Hyderabad which will mass produce and market the candle filter (Vijaya *et al.* 2011).
- *Development of products for detection and removal of pesticide residues*: Nano silver based carbon blocks have been employed for pesticide removal. The nano silver activated carbon block has been developed in collaboration with IIT Chennai and is being marketed by Eureka Forbes as part of its new water purifier, Aquaguard Total (Vijaya *et al.* 2011).
- *Product development of nanoparticle based filtration process for drinking water*: Filter with silver nanoparticles infused in rice husk ash has been used to develop filtration systems for safe drinking water. Potable water is rendered contaminant-free using these systems directly under no energy use. This includes no electricity also thus proving to be of immense use in rural areas where electricity is often a challenge. Thus potable water can be made as safe drinking water in rural areas too.

Tables 5 and 6 summarise the salient features, patent and trademark status of these nano products. These facts indicate the new trend of commercialisation of research outputs from institutions in partnership with private entities and augur well if these useful outputs reach the end users through well-developed product development cycle. These form new sources of livelihood at local levels. Further, it is suggested that these initial successes in drinking water sector be extended as application for ensuring residue-free water in agricultural operations. Overuse of chemicals in agricultural production activities has rendered several water bodies contaminated through leaching of chemicals and often this water is not fit for use in farm operations. Perhaps this is the reason for current focus of some of current projects on developing solutions for detection and remediation of toxic water for farm use (Table 7). Such a focused research through development of nanotechnology based devices or process to augment water resources fit for agricultural use will be of value to sustain agricultural productivity and hence towards enhancing food security.

Table 6: Tabulation of Intellectual Property Portfolio of Point-of-Use Water Treatment Products based on Nanotechnology.

Product	Patent	Trademark	Reference
Puritech™	• Application No.: 2786/ DEL/2005 • Filing date: 19.10.2005 • Publication date: 26.12.2008 • Status: Application is under examination. • IPC: B22F1/00	• Registered trademark. • Good & Service detail: Class11	http://ipindiaservices.gov.in/patentsearch/ http://ipindiaservices.gov.in/eregister/eregister.aspx
Tata Swach® Nanotech Water Purifier	• Application No.: 1576/ MUM/2008 • Filing date: 24.07.2008 • Publication date: 29.01.2010 • Status: Application under examination • IPC: C02F1/00 • PCT Filing: WO2008IN00826 • Citations: Cited:8; Citing 0	• Registered Trademark • TM Application No.: 1839922 • Publication date: 17.12.2012 • Good & Service detail- Class11	http://ipindiaservices.gov.in/patentsearch/ http://ipindiaservices.gov.in/eregister/eregister.aspx
Aquaguard Total™	• Patent granted: IN200767B • Publication date: 23.02.2007 • IPC: C02F1/28 • Patent jurisdictions: IN(2);US(2); EP(3) • Citations: Cited: 6; Citing: 0	• Registered trademark • Good & Service detail: Class11	http://ipindiaservices.gov.in/patentsearch/ http://ipindiaservices.gov.in/eregister/eregister.aspx

Source: Based on data collected from various sources by the authors.

Table 7: Examples of Research Projects Focussing on Nanotechnology for Water Management in Indian R&D Sector

S. No.	Name of Institutes/ University	Nanotechnology project	Reference
1	Punjab Agricultural University, Ludhiana	Nano-technology for Enhanced Utilisation of Native - Phosphorus by Plants and Higher Moisture Retention in Arid Soils.	NAARM 2010.
2	Central Institute of freshwater Aquaculture, Bhubaneswar, Odisha	Nanotechnology in aquaculture; an alternative approaches for fish health management and water remediation	NAARM 2010.
3	Banaras Hindu University, Varanasi	Method to produce carbon nano tube filters that efficiently remove micro-to nano-scale contaminants from water and heavy hydrocarbons from petroleum.	Vijaya *et al.* 2011.
4	Bhabha Atomic Research Centre (BARC), Mumbai	Carbon nano tube based water filters	Kar S. *et al.* 2008.
5	Indian Institute of Technology (IIT), Kharagpur	Synthesised iron oxide particles using chemical method for arsenic removal from water	De D. *et al.* 2009.
6	Indian Institute of Technology (IIT), Mumbai	Surface engineered nano particles for the detection and separation of toxic metal and organic dyes from water	Vijaya *et al.* 2011
7	Indian Institute of Technology (IIT), Delhi	Nanostructured sensors for water related safety and security	Vijaya *et al.* 2011

Source: NAARM (2010).

From the foregoing discussion in this section, it is clear that the involvement of the emerging economies in addressing concerns of water availability and pollution, by including the possible use of nanotechnologies, is increasing rapidly. It is essential to point that most of these countries including India depend on an agrarian economic structure. The initial efforts of R&D sector in China, Brazil, India, Israel, and Russia in developing nanotechnology research in exploring its potential in augmentation of water, an essential resource in agriculture, indicate the need of such technology for addressing concerns in food and nutritional security. Such investments in

R&D in the public sector and also by private institutions also indicate the interest of all stakeholders in exploring new developments in nanoscience. However, it is important that policies in these economies be framed to ensure that involvement of scientists from these countries through partnership with other developing countries like Singapore and South Africa (which have made major investments in this research). These efforts could help to balance the demand for global up-market products and services in this sector and also the local needs of the developing regions. The direct involvement of emerging and developing countries in water research and in collaboration with research institutes and industries in developed countries can help to facilitate an equitable and efficient sharing of knowledge and competencies (OECD 2011) and will in the longer term assist developing countries to more easily adopt new technologies.

Conclusion

The development of technologies for the provision of clean and plentiful supplies of freshwater is central to water security and food and nutrition security. The potential of nanotechnology in terms of advancing water security is very exciting and awaits exploration. Water purification, waste water treatment, remediation, irrigation, water quality measurement and soil moisture detection are identified as the major determinants of water security in India. Emerging nanotechnologies can be focused on these key determinants to catalyse the research and develop a sustainable water security system.

The current trends in nanotechnology were assessed for their potential to enhance water security using R&D indicators like literature and patents mapped in a specially designed framework. The study indicated that nanotechnology has a large canvas and great potential to address water security as compared to conventional methods and technologies. This is because of some unique features of nanomaterials like their large surface area and their size- and shape-dependent catalytic properties permit their use in applications such as membrane separations, catalysis and adsorption. Novel nanomaterials, particularly in water and wastewater treatment, are expected to play key roles in ensuring sufficient and good quality water to meet the ever-increasing demand for potable water in agriculture and human welfare. However, it is emphasised that more science based evidence on possible risks on the environment, health and their impacts on the social structure be undertaken through R&D. There is a need to encourage dialogue between stakeholders in developing and industrialised countries, among stakeholders in the emerging economies like India and China which have major role in addressing national food security concerns, and among sectors that can provide constructive approaches for addressing the implications of nanotechnology for the augumenting water for agriculture. Equaly it is important that more investments for trained manpower and in R&D sector be made if the promise of nanotechnology in enhancing water security concerns in agriculture sector is to be effectively harnessed.

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RIS
Research and Information System
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Asian Biotechnology and Development Review
Vol. 15 No.3, pp 37-49

Health Hazards Associated with Engineered Nanomaterials

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Abstract: Engineered nanoparticles (ENPs) are being increasingly produced as a result of the rapid development in nanotechnology. They are used to generate innovative and versatile goods in a wide range of industrial, medical and public sectors including healthcare, biomedicine, cosmetics, agriculture, transport, energy, materials, and information and communication technologies. Nanomaterials have very unique chemical and physical properties that do suggest potential health hazards, but a limited health and safety information exists for engineered nanomaterials. In vivo and in vitro experimental studies have shown that several types of ENPs (metallic nanoparticles, quantum dots, carbon nanotubes, Zinc oxide, Iron oxide) can have various types of biological effects, some detrimental on the various organs, both acutely and in the long term, resulting in cytotoxicity and/or genotoxicity. This review focus on the possible biological impact of engineered NPs, serving as a reminder that nanomaterials can become a double-edged sword if not handled properly and thus, the current efforts should include research to generate data for safety and nanotoxicological evaluation of potential or putative hazards to the human health in particular and the environment at large.

Key words: Engineered nanoparticles, cytotoxicity, genotoxicity, carbon nanotubes, hazards

Nanotechnology has been defined by the US National Nanotechnology Initiative (NNI) as “understanding and control of mater at dimensions of roughly 1 to 100nm (nanomaterials) where unique phenomena enable novel applications” (NNI 2007). The term nanomaterials is used to describe materials with one or more components that have at least one dimension in the range of 1 to 100 nm and include nanoparticles (NPs), nanofibres and nanotubes, composite materials and nano-structured surfaces. They,

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for example, include Gold NPs, Carbon NPs, Europium oxide NPs, Titanium NPs, Magnetic NPs, Biodegradable NPs (PLGA), Nanotubes (singled-walled and multi-walled), Nanowires, Fullerene derivatives, Quantum dots, etc. Research on toxicologically relevant properties of these engineered nanomaterials has increased tremendously during the last few years. Nanomaterials may have different properties like chemical, optical, magnetic, and structural; hence consequently they have differential toxicity profiles (Lanone and Boczkowski 2006; Studart *et al*. 2007). 'Engineered nanomaterials' (ENMs) are nanomaterials with specific physico-chemical characteristics manufactured intentionally by humans. Nanomaterials hold great promise in a range of biomedical applications, including medical imaging and diagnostics and for targeted delivery of therapeutic compounds, or the simultaneous monitoring of disease processes and therapeutics (theranostics). ENMs are intentionally designed, which have application in nanomedicine and are monodispersed and are in solid form, whereas unintentional nanosized particles are polydispersed and chemically complex (Oberdorster *et al.* 2005 and Moghimi *et al.* 2005). However, the same toxicological principles apply to unintentionally and intentionally designed nanoparticles (Oberdorster *et al.* 2005).

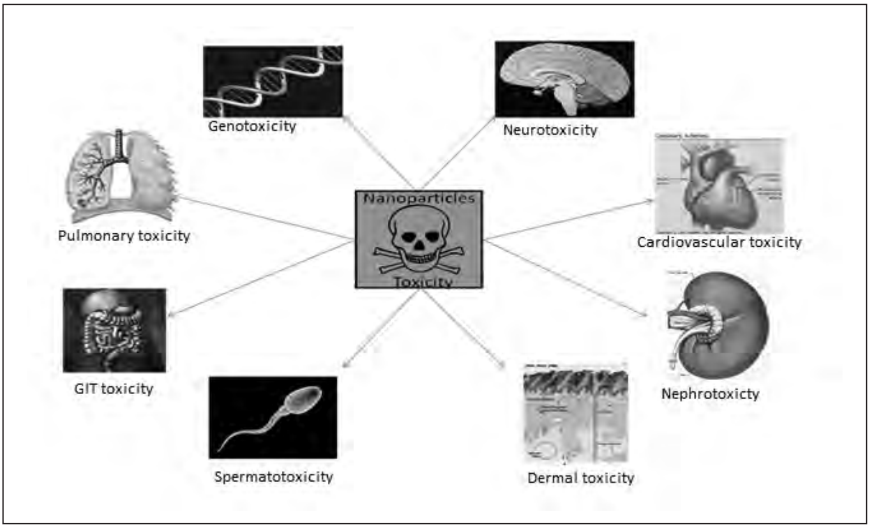
Nanomaterials being a potent toxin they affect almost all the tissues which come in contact with them as shown in Figure 1.

Nanotoxicology refers to the study of the interactions of nanostructures having biological systems with an emphasis on elucidating the relationship between the physical and chemical properties of nanostructures with induction of toxic biological responses (Oberdorster *et al.*, 2005). Mammal's skin, lungs and the gastro-intestinal tract are in constant contact with the environment. The lung and gastro-intestinal tract are more susceptible compared to the skin because it has effective barrier to foreign substances. These three are the most critical points of entry for natural or anthropogenic nanoparticles. Injections and implants are other minor possible routes of exposure, primarily limited to engineered materials.

Entry of Nanoparticles into Living System

Possible routes of entry into the body include inhalation, absorption through the skin or digestive tract, injection, and absorption or implantation for drug delivery systems. In particular, nanoparticles uptake by inhalation and ingestion are likely to be the major routes in terrestrial organisms (Brigger *et al.* 2002).

Figure 1: An Interdisciplinary Science: Nanotoxicology



Note: An overview of the potential toxic effects associated with nanomaterials, *in vivo* and *in vitro*. Figure showing the different toxicity due to nanomaterials like genotoxicity, neurotoxicty, pulmonary toxicity, cardiovascular toxicity, gastro-intestinal tract (GIT) toxicity, nephrotoxicity, spermatotoxicty and dermal toxicity.

Source: Modified from El-Ansary and Al-Daihan 2009.

Respiratory Tract

The respiratory tract can be divided into three regions: nasopharyngeal, tracheobronchial, and alveolar. Significant amounts of certain particle size ranges can deposit in each region; for example, about 50 per cent of nanoparticles of 20nm in diameter deposit in the alveolar region and remaining 15 per cent in the nasopharyngeal region, 15 per cent in the tracheobronchial region. In comparison, nanoparticles of 1nm size do not reach the alveolar region and about 90 per cent deposit in nasopharyngeal region and 10 per cent in the tracheobronchial region (Moghimi *et al.* 2005). Inhaled nanoparticles are deposited in all regions of the respiratory tract, but only smaller particles reach distal airways and larger particles may be filtered out in the upper airways (Curtis *et al.* 2006 and Hagens *et al.* 2007). The nanoparticels are absorbed across the lung epithelium and enter into the blood and lymph to reach cells in the bone marrow, lymph nodes, spleen, and heart. Diesel exhaust (DE) and DE particles (DEP) are one of the major compounds responsible for air pollution. These compounds consist of nanopaticles which induce adverse health effects. Several studies reported that the effects of nanoparticles on the human body (mammals) have shown that nanoparticles exacerbate lung injury. When the nanoparticles are administered through the nasal, they accumulate in the brain via the olfactory nerve and exacerbate inflammatory reactions (Elder *et al.* 2006). Nanoparticles also affect the circulatory system by altering heart rate (Chalupa *et al.* 2004).

Nanomaterial Toxicity: Mechanism of Action

Nanomaterials have unique properties and characteristics of high surface area to volume ratio, hence results into a unique mechanism of toxicity. In particular, toxicity has been thought to originate from nanomaterial size, surface area, composition, and shape as reviewed by Lanone and Boczkowski (2006). Size of the particle can also affect the mode of endocytosis, cellular uptake, and the efficiency of particle processing in the endocytic pathway (Lanone and Boczkowski 2006 and BeruBe *et al.* 2007). As the particles size decreases then it leads to an exponential increase in surface area relative to volume, which makes the nanomaterial surface more reactive on itself (aggregation) and to its surrounding environment (biological components). This activity includes a potential for inflammatory and pro-oxidant, which explain early findings showing mixed results in terms of toxicity of Nano Sized Particles (NSPs) to environmentally relevant species. When the nanomaterial uptake is increased into certain tissues then it may lead to accumulation, where they may interfere with critical biological functions (Lanone and Boczkowski 2006 and Sayes *et al.* 2007). The chemical interaction of the nanomaterial at the surface is largely defined by the chemical composition, since the surface is in direct contact with the body whereas the limited bulk volume is hidden.

The main molecular mechanism of *in vivo* nanotoxicity is the induction of oxidative stress by free radical formation and these free radicals will also cause damage to biological components through oxidation of lipids, proteins and DNA. This leads to more oxidative stress on the body which have a role in the induction or the enhancement of inflammation through-up regulation of redox sensitive transcription factors (e.g. NF-κB), activator protein-1 and kinases involved in inflammation. Interactions of nanomaterials with the mitochondria and cell nucleus are being considered as main sources of toxicity. The organs like liver and spleen are the main targets of oxidative stress because of slow clearance and accumulation (storage) of potential free radical producing nanomaterials as well as prevalence of numerous phagocytic cells in the organs of the reticuloendothelial system (RES). Additionally, organs of high blood flow that are exposed to nanomaterials, such as the kidneys and lungs, can also be affected.

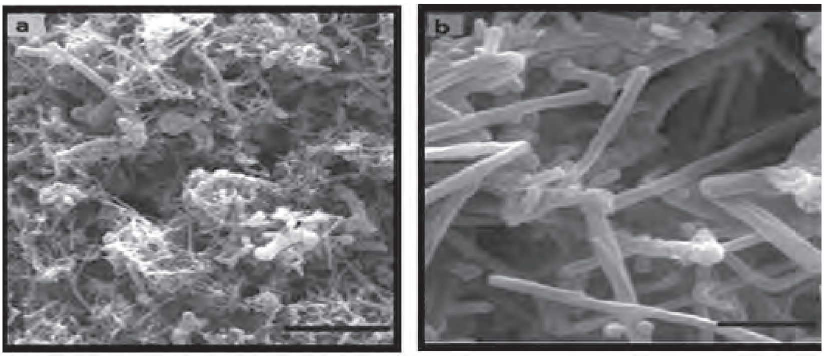
Carbon Nanotubes (CNTs)

Three types of single walled carbon nanotubes (SWCNTs) were investigated in an intratracheal instillation (study in mice) (Lam *et al.* 2004). The results showed that regardless of the amount of metal impurities, dose-dependent lung lesions were characterised chiefly by interstitial granulomas and SWCNTs were taken up by alveolar macrophages. In macrophages SWCNTs clustered to form granulomas in centrilobular locations. Muller *et al.* (2005) compared the pulmonary toxicity of ground and unground multi-walled carbon nanotubes (MWCNTs) in rats, using asbestos (Rhodesian chrysotile) and carbon black as references. They found that after 60 days there were indications of a higher degree of pulmonary inflammation with ground MWCNTs than that with intact MWCNTs-treated animals. They also noticed that the adverse effects of MWCNTs depend on the length of the material used *in vivo*. Scanning electron microscope (SEM) images of MWCNTs scaffold prepared in our lab on polyethyleneimine-coated glass surface at different magnifications and different views are shown in Figures 2 (a) and (b). The topological features of nano-network assembly and the surface modification by protein adsorption served to convert CNTs into a bioactive material with pronounced cell growth and functional activities (Rafeeqi and Kaul 2010a and 2010b).

Zinc, Iron and Selenium Nanoparticles

Cha *et al.* (2007) exposed zinc (300 nm), iron (100 nm), selenium (10-20, 40-50, 90-110 nm; 0.24–2400 _ 1029 g ml21) nanoparticles to glioma cell line. Results showed that the nanoparticles did not alter the membrane permeability and the cytotoxicity *in vitro* was low. Moreover, it was not dependent on the types and the sizes of nanoparticles and thus here the toxicity was inferred to be due to material chemistry rather than size (Cha *et al.* 2007).

Figures 2 (a) and (b): Scanning Electron Microscopy Images of MWCNTs Scaffold.



Note: When observed by SEM at different magnifications and different views, these scaffolds with compact structure were composed of many thousands of highly entangled nanotubes with diameters ranging from nm to several micrometers in length. SEM micrographs show MWNTs distributed all over the surface. Scale bars represent (a) 5 µm (b) 1 µm.

Source: Rafeeqi and Kaul 2010a.

Fe_2O_3 Magnetic Nanoparticles

The temporary exposure to Fe_2O_3 magnetic nanoparticles (MNPs) results in a dose-dependent reduced ability of rat pheochromocytoma (growing neuron cell line PC12) to respond to nerve growth factor (NGF). PC12 cells exposed to different doses of Fe_2O_3 MNPs show reduced viabilities, increased cytoskeletal disruption, decreased intracellular contact, and diminished ability to form mature neuritis in response to NGF exposure as compared to control cells (Pisanic II *et al.* 2007).

Magnetic Nanoparticles

The effect of magnetic nanoparticles on the adhesion and cell viability concerned to astrocytes was assessed by Au *et al*. (2007). They observed that nanoparticles impede the attachment of astrocytes to the substratum. However, once astrocytes attach to the substratum and grow to confluence, nanoparticles may cause mitochondrial stress. Due to lack of a significant difference between the control and nanoparticle-treated group strongly suggests that the addition of nanoparticles to astrocytes does not disturb membrane integrity.

Effect of Nanoparticle on Spinal Cord

When SWCNTs exposed to chicken embryonic spinal cord or dorsal root ganglia, the DNA content is significantly decreased. This effect was more pronounced when cells were exposed to highly agglomerated SWCNTs than when they were exposed to better dispersed SWCNT bundles (Belyanskaya *et al.* 2009).

Gold Nanoparticles

Wiwanitkit *et al*. (2008) evaluated the effect of gold nanoparticles on RBC *in vitro*. Mixture of gold nanoparticle solution and blood sample was analysed. Accumulation of gold nanoparticles in the red blood cell was observed but there was no significant destruction of the red blood cell.

Carbon Nanotubes, Zinc Oxide and Iron Oxide Nanoparticles

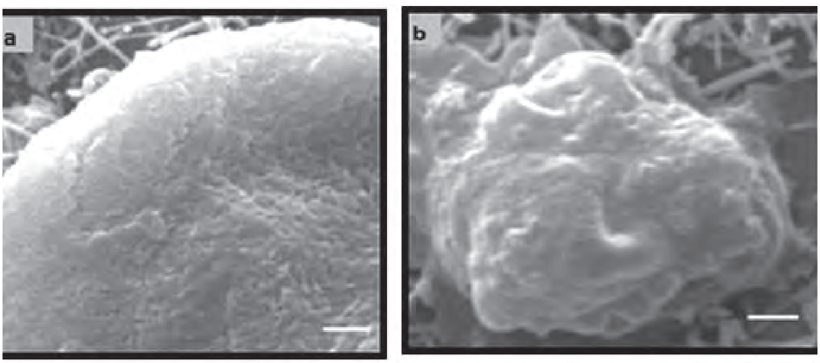
Loeb *et al*. investigated the toxic effect of MWCNTs, zinc (II) oxide (ZnO) and iron (III) oxide (Fe_2O_3) nanomaterials on human red blood cells (RBC). Hemolysis of erythrocytes is a useful method to examine the effects of particles on the cell membrane. The interaction of RBC and nanoparticles were studied with the help of ultra high resolution imaging systems. This unveiled attachment of nanoparticles to RBC and their cross linking effects. And MWCNTs were able to induce only hemolysis where as Fe_2O_3 displayed only hemagglutination, and ZnO nanorods showed both hemolysis as well as hemagglutination. It showed that the MWCNTs, ZnO and Fe_2O_3 are toxic to human red blood cells, irrespective of the blood group.

Cells of Reproductive System: Effect of Nanoparticles on Testis

Carbon Black Nanoparticles (CB)

The *in utero* effect of CB on the reproductive function of male offspring was investigated by Yoshida *et al*. (2010). They administered CB *in utero* and observed that the daily sperm production (DSP) was significantly reduced in male offspring. Even when CB was administered to adult mice, DSP decreased significantly (Yoshida *et al.* 2009). When adult mice were exposed to CB, the incidence of seminiferous tubule damage was high (vacuolation of the seminiferous tubules); however, its severity was mild (Yoshida *et al.* 2009). The intercellular adhesions of seminiferous epithelia and seminiferous tubules damage were observed in testis of male offspring and thus inhibited the spermatogenesis. Figures 3 (a) and (b) show the spermatogonial stem cells cultured on multi-walled carbon nanotube and functional multi-walled carbon nanotube scaffold, pre-prepared on polyethyleneimine-coated glass surface. The SEM images showed that the spermatogonial stem cells had adhered properly and extensions of the cell were seen in all directions on carbon nanotube scaffolds. The results provided the degree of biocompatibility between spermatogonial cells and CNTs, and the real possibility for CNTs to be used as an alternative nano-material for *in vitro* growth of these cells (Rafeeqi and Kaul 2010c).

Figures 3 (a) and (b): Higher Magnification SEM Images of Germ Cells during *in vitro* Culture on MWCNTs and Functionalised MWCNTS



Note: The cell body maintaining its shape and adhering properly with substratum. Scale bars represent (a) 1 µm and (b) 2 µm.

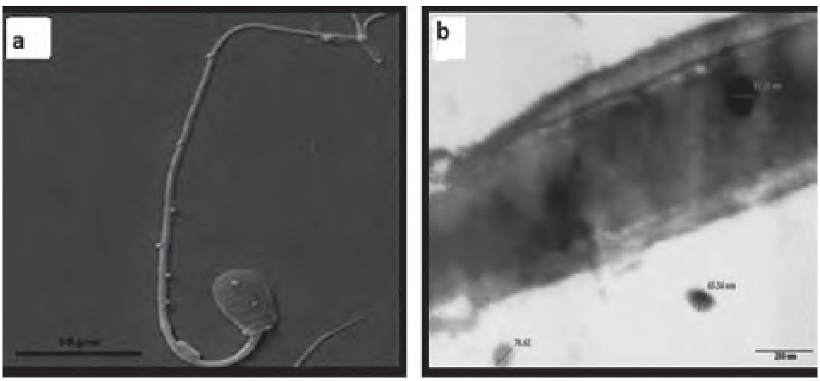
Source: Rafeeqi and Kaul 2010c.

Titanium Dioxide (TiO_2) and Zinc Oxide Nanoparticles

Gopalan *et al.* (2009) assessed the effects of ZnO and TiO_2 nanoparticles (40-70 nm range) in the presence and absence of Ultra-Violet (UV) light in human sperm and human lymphocytes in the dark (D), after pre-irradiation with UV (PI) and simultaneous irradiation with UV (SI). The effect of TiO_2

nanoparticles showed that the percentage reduction in head DNA was greater for PI and SI samples compared with samples treated in the dark. However, with regard to photogenotoxicity, sperm exhibited no significant differences when the results for PI and SI and the dark were compared, except at the lowest concentration for SI samples in the case of ZnO and the lowest concentration for PI in the case of TiO_2. Scanning electron microscopy of spermatozoa loaded with the TiO_2 nanoparticles revealed attached TiO_2 nanoparticles on the surface/membrane of spermatozoa (head and tail both) and TEM pictures revealed the presence of nanoparticles attached on and inside the head and tail region (Figures 4 (a) and (b)).

Figures 4 (a) and (b): Scanning Electron Microscopic (SEM) Photographs of Buffalo Spermatozoa.



Note: (a) Spermatozoa mixed with nanoparticle showing nanoparticles attached on the membrane of tail and head. (b) Transmission electron microscopic photographs of buffalo spermatozoa (head region) incubated with TiO_2 nanoparticles for 6 hours. Longitudinal section of sperm.

Source: Pawar and Kaul 2010.

Effect of Nanoparticles on Leydig Cells

Diesel Exhaust Particle (DEP), Carbon Black and TiO_2 Nanoparticles

Komatsu *et al.* investigated the effect of Diesel Exhaust Particle (DEP), carbon black (CB) and TiO_2 on mouse Leydig TM3 cells, (the testosterone-producing cells of the testis). They assessed that TiO_2 was more cytotoxic to Leydig cells than other nanoparticles. The proliferation of Leydig cells was suppressed transiently by treatment with TiO_2 or DEP. When mouse Leydig

TM3 cells were treated with DEP then the expression of heme oxygenease-1 (HO-1) a sensitive marker for oxidative stress was induced remarkably. The gene expression of the steroidogenic acute regulatory (StAR) protein, the factor that controls mitochondrial cholesterol transfer was slightly increased when exposed to CB and DEP. Hence, overall results were found that DEPs, TiO_2 and CB nanoparticles were taken up by Leydig cells, and affected the viability, proliferation and gene expression.

Effect of Nanoparticles on Ovarian Granulosa Cells

Liu *et al*. (2010) investigated the effect of calcium phosphate nanoparticles on both steroid hormone production and apoptosis in human ovarian granulosa cells. Results showed that calcium phosphate nanoparticles could enter into granulosa cells, and distributed in the membranate compartments, including lysosome, mitochondria and intracellular vesicles. Treatment with calcium phosphate nanoparticles at concentrations of 10-100 mM didn't significantly change either the progesterone or estradiol level in culture fluid, and the expression levels of mRNAs. Liu *et al.* (2010) concluded that the calcium phosphate nanoparticles interfered with cell cycle of cultured human ovarian granulosa cells thus increasing cell apoptosis.

Carbon Nanotubes

The effect of SWCNTs on primary immune cells *in vitro* was investigated by Zhang *et al.* (2008). The results showed that SWCNTs (25 and 50 mg/mL) could promote the proliferation of spleen cells but not at concentrations of 1 and 10 mg/mL. Interestingly, they can inhibit T-lymphocyte proliferation at higher concentrations but have no effect on T-lymphocyte proliferation stimulated by concanavalin-A (ConA) at lower concentrations. They also observed that SWCNTs inhibited the B-lymphocyte proliferation stimulated by lipopolysaccharides (LPS) at concentrations of 1, 10, 25 and 50 mg/mL. Authors concluded that SWCNTs have possibly negative effects on immune cells *in vitro*.

Conclusion

Several researches were carried out with different nanoparticles causing abiotic stress on the animal and human health. This shows us that engineered nanoparticles must be handled with care and workers exposure must be minimised, since these effects are extremely variable from one product to another. Although studies are conflicting regarding the magnitude and mechanisms of nanomaterial toxicity, it is evident that some nanomaterials that were previously considered biocompatible due to safety of the bulk material may indeed be toxic. Still the pharmaco-kinetic behaviour of different types of nanoparticles requires detailed investigation and a database of health risks associated with different nanoparticles (e.g. target organs, tissue or cells) should be created. Existing research on nanotoxicity has concentrated on empirical evaluation of the toxicity of various nanoparticles, with less regard given to the relationship between nanoparticle properties (exact composition, crystallinity, size, size dispersion, aggregation, ageing, etc.) and their toxicity in the mammals. This approach gives very limited information, and should not be considered adequate for developing predictions of toxicity of seemingly similar nanoparticle materials. The studies must include research on nanoparticles translocation pathways, accumulation, short- and long-term toxicity, their interactions with cells, the receptors and signalling pathways involved, cytotoxicity, and their surface functionalisation for an effective phagocytosis in the mammals. Hence there is a serious lack of information concerning the human health, animal health and environmental implications of manufactured nanomaterials. Understanding the interactions of these "new age materials" with biological systems is key to the safe usage of these materials in novel biomedical fields like diagnostics and therapeutics. Since these are relatively new particles, it requires thoughtful environmental, human health, animal health and safety research, meaningful and an open discussion of broader societal impacts, and urgent toxicological oversight action.

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RIS
Research and Information System
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Asian Biotechnology and Development Review
Vol. 15 No.3, pp 51-66

Developments in Bionanocomposite Films: Prospects for Eco-friendly and Smart Food Packaging

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Abstract: Food packaging is an important factor in maintaining the quality of the food. The environmental concerns on using synthetic petrochemical based packaging materials due to their non-biodegradable nature necessitated in developing biodegradable films from natural polymers such as cellulose, starch, gelatin and chitosan. However, owing to their inherent limitations of poor mechanical and barrier properties, the bio-polymer based packaging films could not replace the synthetic packaging materials. The need to improve the properties of these biopolymer films has been fulfilled by nanotechnology interventions leading to the development of nanocomposite films incorporated with nano materials in the form of either nano-fibers or nano-whiskers. In last decade, several bionanocomposite films have been developed and evaluated for food packaging. Recent advances in the development of food packaging films allowed integrating bioactive molecules (active packaging) to extend the shelf-life of food and incorporating biosensors (smart packaging) to recognise spoilage of food. Additional efforts are needed for commercial production of bionanocomposite films to realise the importance of food packaging in reducing the colossal wastage of food and food products without causing any environmental concerns.

Key words: Active packaging, biodegradable film, edible film, nanomaterials, biopolymer, nano clay

Introduction

In our everyday life, we encounter different types of food packaging materials having various functions. The food packaging materials are carefully designed to undertake a number of roles to present food to us in an attractive, safe and most convenient manner. The advances in food packaging are able to increase food shelf life by avoiding spoilage and

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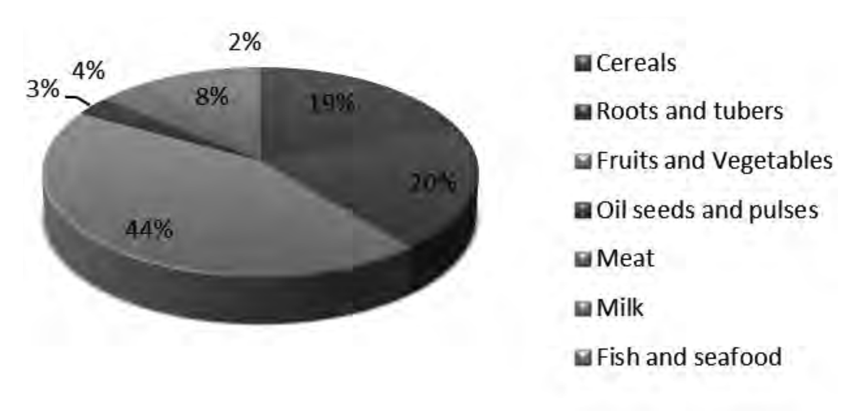
Authors are thankful to the Director, Central Institute of Fisheries Education, Mumbai for his support and encouragement.

loss of nutrients. According to estimates of the Food and Agriculture Organisation of the United Nations, 32 per cent of all food produced in the world, amounting to 1.3 billion tonnes, was either lost or wasted in 2009 (FAO 2011). As per the figures available commodity wise, fruits and vegetables constitute the maximum of 44 per cent, followed by roots and tubers (20 per cent) and cereals (19 per cent) (Figure 1).

Figure 1: Global Food Loss and Waste by Commodity



Source: FAO, 2011.

The practice of food packaging has its existence from the initial days of the human evolution. The form of food packaging gets changed over the time by the technological developments and the societal requirements. The form of food packing thus ranged from animal leather, wood, earthen pots, glass, steel, tin coated steel, etc., for the past so many years. Only during the last century the use of plastics has become available in the food industry. In comparison with the rigid containers, plastics are more advantageous as they are light in weight, transparent in colour, can be used in microwave ovens, etc. (FAO 2012). Because of their multiple benefits in terms of convenience and protection of food, the flexible packaging films have replaced almost all other food packaging materials and dominate the industry.

Pros and Cons of Plastic-based Packaging Materials

At present scenario, the largest part of materials used in the packaging industry is plastic-based produced from either fossil fuels or synthetic polymers. They are highly advantageous in terms of cost effectiveness, mechanical properties like tensile strength and barrier properties. The flexible nature of these plastics also helps in the effective packaging of food items to reduce storage and transportation space requirement significantly. On the other side, they pose high risk to the environment as they are practically un-degradable (Kirwan and Strawbridge 2003). It has been estimated that 500 billion to one trillion plastic bags are used and discarded annually worldwide. In other words, more than a million plastic bags are accumulated as waste per minute. Other concerns include the release of toxic pollutants and death of animals by mistakenly consuming plastics as food. By realising the negative effects of plastics and their detrimental effects on the environment, several countries such as the US, Japan, Ireland, etc., have raised a ban on using the plastic bags to minimise their adverse effects on environment.

The Ministry of Environment and Forests (MoEF), Government of India issued the ‘Recycled Plastics Manufacture and Usage Rules, 1999’ under the Environment (Protection) Act, 1986 with the dual objective of containing environmental problems caused by the littering of plastic carry bags, and health problems arising from consumption of ready-to-eat foodstuff in plastic bags made from recycled material. The Rules banned the manufacture, storage, sale and/or use of plastic carry bags having less than 20-micron (20-micron equivalent to 0.2 mm) thickness. Thereafter, in an amendment of the Plastic Rules issued in 2003, the MoEF prohibited the manufacture, sale and use of carry bags below the size of 8” x 12” (20 cm x 30 cm).

Shift Towards Biopolymer-based Food Packaging Materials

The increasing environmental concern on indiscriminate use of plastic packaging materials and the necessity to extend the shelf life and enhance food quality has led to the development of new biopolymer based packaging materials, such as edible and biodegradable films from renewable resources (Tharanathan 2003). These biopolymer based packaging materials, due to their biodegradable nature, are expected to solve the environmental concern to a greater extent.

Biodegradable polymers can be of different categories: Polymers directly extracted from biomass (polysaccharides, proteins, polypeptides, polynucleotides); polymers produced by chemical synthesis using renewable bio-based monomers or mixed sources of biomass and petroleum (polylactic acid or bio-polyester); and polymers produced by micro-organism or genetically modified bacteria (polyhydroxybutyrate, bacterial cellulose, xanthan). Though biodegradable polymers are eco-friendly, they have not been in use as expected due to their inherent poor properties. In particular, brittleness, low heat distortion temperature, high gas and vapour permeability, and poor resistance to heavy processing conditions have strongly limited their applications (Table 1). Hence the need was felt to improve their properties especially mechanical and barrier properties to make them on par with the existing petrochemical based films.

Table 1: Advantages and Limitations of Biopolymer-based Packaging

Benefits	**Limitations**
Biodegradable and environment friendly	Poor barrier property
Can be made edible	Less tensile strength
No release of toxic substances	brittle
No alteration in the inherent properties of food	low heat distortion temperature
Can be added with active components	high gas and vapour permeability
Waste utilisation	poor resistance to heavy processing conditions

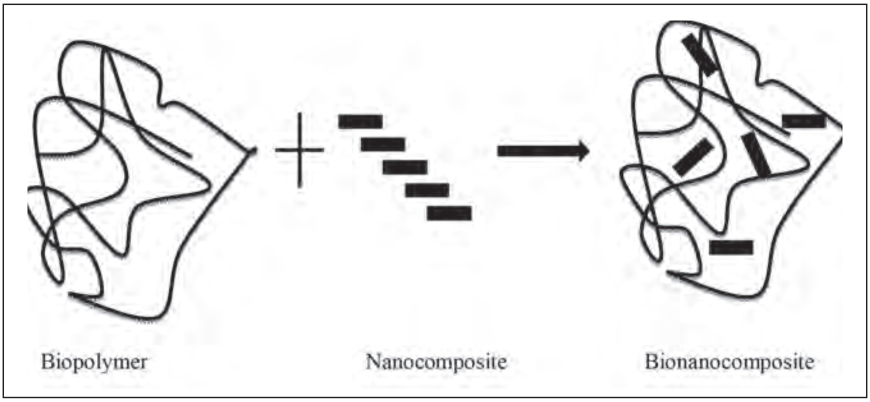
Source: Analysis by authors.

Nanotechnology in Production of Eco-friendly Food Packaging Materials

Incorporation of nanomaterial while developing the packaging material has been reported to improve significantly the physical, mechanical, barrier, optical and recycling properties. Also, the use of nanocomposites promises to expand the use of edible, biodegradable films produced from natural byproducts developed during the agro-processing. They have the potential of improving the properties of the films as well as with the addition of some preservative agents; they can extend the shelf life of the food delaying the onset of spoilage.

Nanocomposite is a combination of nano-sized filler materials, which are interlaced/incorporated in the matrix of natural/synthetic polymers (Figure 2). Generally, it can be of particles, fibres or fragments which are surrounded by the polymer matrix which makes the composites more strong and flexible as well. Nanocomposites with synthetic polymer matrix like reinforced plastic, fiberglass, etc., are available for use in different areas. The nanocomposites with natural polymers, known as bionanocomposites, are gaining importance in recent times. Though there have been a variety of nanocomposite materials available for other applications, the development of nanocomposites assumes significance in food packaging.

Figure 2: Preparation of Bionanocomposite



Source: Authors expression.

Nanocomposites can improve mechanical, thermal, barrier and physico-chemical properties, when compared with the conventional microsized composites. They show great barrier properties, due to the presence of the clay layers that are able to delay the molecule pathway making the diffusive path more tortuous (Bharadwaj 2001; Sorrentino *et al*. 2006). Many researchers reported the effectiveness of nanoclays in decreasing oxygen (Bharadwaj *et al*. 2002; Cabedo *et al*. 2006; Koh *et al*. 2008; Lagaron *et al*. 2005; Lotti *et al*. 2008) and water vapour permeabilities (Bharadwaj 2001; Jawahar and Balasubramanian 2006; Lotti *et al*. 2008; Mangiacapra *et al*. 2005).

Bionanocomposites: A New Era in Food Packaging

The development of biodegradable packaging films for food packaging has been getting significance over a few years and the incorporation of nanocomposites into that is the novelty in the recent years with the developing spur of nanotechnology. Bionanocomposites can be used to extend the shelf-life of the fresh products such as fruits and vegetables by controlling respiratory exchange. They can also improve the quality of fresh, frozen, and processed meat, poultry, and seafood products by retarding moisture loss, reducing lipid oxidation and discoloration, enhancing product appearance, and reducing oil uptake by battered and breaded products during frying (Box 1). As a result, a number of natural biodegradable materials such as cellulose, starch, gelatin, chitosan, etc., have been investigated for use with the incorporation of nanocomposites. The biodegradable nanocomposites possess not only properties of the films, but also extend the shelf life of the food wrapped in it.

Box 1: Benefits of Bionanocomposites in Food Packaging

- Environment friendly and biodegradable in nature
- Edible
- Enhances the shelf life of food
- Improves food quality and properties
- Enhanced barrier properties against oxygen and moisture
- Protection against rancidity of lipid
- Facilitates incorporation of active agents (antioxidants, antimicrobials)
- Possible in controlled use of active agents
- Possible use in multilayer food packaging materials together with non-edible films
- Supports the use of biosensors and nanochips for food quality assessment
- Low cost and effective waste utilisation

Cellulose-based Nanocomposite Films

Cellulose is the most abundantly occurring natural polymer on earth and is a linear polymer of anhydroglucose. Though it is a cheap polymer, it is difficult to develop cellulose-based films because of its hydrophilic nature, insolubility and crystalline structure. To make cellulose or cellophane film, it is dissolved in a mixture of sodium hydroxide and carbon disulphide and then recast into sulphuric acid. The cellophane produced is very hydrophilic and, therefore, moisture sensitive. It is often coated with nitrocellulose wax or poly-vinylidene chloride to improve barrier properties. However, there is considerable potential for the development of an improved cellulose film or an improved production method as the existing product is problematic. Cellulose can be used as base polymer in preparation of composite films. Also, it can be used as the nano fillers in the form of cellulose nanowhiskers or nano fibres. Cellulose nanowhiskers from cotton fibres have been prepared and characterised by Satyamurthy *et al*. (2011).

Starch-based Nanocomposite Films

Starch is a better candidate for the preparation of thermoplastic foam type packaging materials. Several studies have been carried to improve the mechanical and hydrophobic properties of the thermoplastic starch by adding natural fibres, plasticizers, synthetic degradable polymers and acetylated starches. De Carvalho *et al*. (2001) prepared and characterised thermoplasticised starch-kaolin nanocomposites by melt intercalation techniques. Significant increase in tensile strength up to 70 per cent was observed by Wilhelm *et al*. (2003) in cara root starch/hectorite nanocomposite films at a 30 per cent clay level. Park *et al*. (2002) found that the films produced by potato starch/montmorillonite (MMT) nanocomposites increased the tensile strength by 25 per cent and decreased the water vapour transmission rate by 35 per cent. Subsequently, Avella *et al*. (2005) reported the development of potato starch/MMT nanocomposite films for food packaging applications with improved mechanical properties. Several other researchers also reported the advantages of starch/clay nanocomposite films (Pandey and Singh 2005; Huang *et al*. 2006; Chiou *et al*. 2007). Recently, Tang *et al*. (2008) developed nanocomposite films with starch and MMT composite and the results showed higher tensile strength and better water vapour barrier properties than control film.

Gelatin-based Nanocomposite Films

Gelatin can be used as the film forming material in developing edible biodegradable films. As it is extracted from animal and fish waste, it helps in waste utilisation as well. Nano-scale silver particles and Zinc Oxide (ZnO) are used in the films to improve their properties. In addition, the use of natural preservatives in food packaging materials provided an additional advantage to improve the shelf life of foods. Hence, it is highly desirable to utilise gelatin for developing a practically applicable food packaging material, which is environmental friendly as well as protective to the food product by using the nanotechnology.

Nano-scale silver particle stabilised by gelatin was prepared by Halder *et al*. (2011) and evaluated by transmission electron microscope (TEM). TEM micrographs showed the presence of nanoscale silver particles of 3.9 nm size. Their study revealed that the nanocomposites exhibited significant antibacterial and antifungal activity. Recently, Kanmani and Rhim (2014) developed gelatin/silver nanoparticle (AgNPs) composite films and reported that the increase in the concentration of AgNPs resulted in a substantial decrease in water vapour permeability (WVP) of the gelatin films and also the films exhibited strong antibacterial activity against food-borne pathogens. Rouhi *et al*. (2013) prepared fish gelatin-based nanocomposites by adding ZnO nanorods (NRs) as fillers to aqueous gelatin. Their results showed an increase in Young's modulus and tensile strength of 42 per cent and 25 per cent for nanocomposites incorporated with 5 per cent ZnO NRs, respectively, compared with unfilled gelatin-based films. The conductivity of the films is found to increase significantly with the addition of ZnO NRs.

Chitosan-based Nanocomposite Films

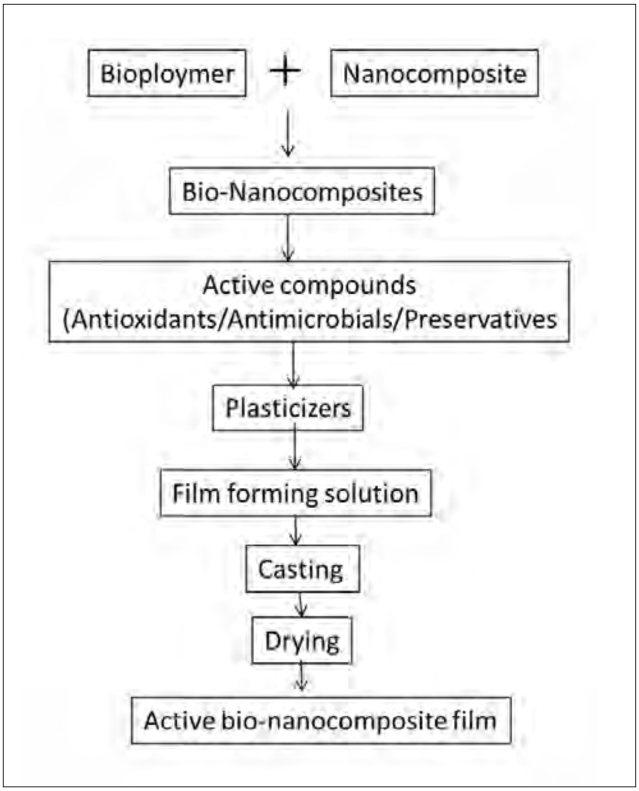
Chitosan is a complex polysaccharide from which nanoparticles can be obtained by ionic gelation, where the positively charged amino groups of chitosan form electrostatic interactions with polyanions employed as cross-linkers, such as tripolyphosphate (Lopez-Leon *et al*. 2005). Chitosan–tripolyphosphate (CS–TPP) nanoparticles were incorporated into hydroxypropyl methylcellulose (HPMC) films which significantly improved mechanical and barrier properties of the films (DeMoura *et al*. 2009). Several authors (Lu *et al*. 2004; Sriupayo *et al*. 2005) worked on the chitosan nano whiskers by hydrolysing chitin. Lu *et al*. (2004) found that chitin whiskers with soy protein isolate (SPI) thermoplastics improved the tensile properties (tensile strength and elastic modulus) of the matrix, as well as the water resistance. Sriupayo *et al*. (2005) found that adding chitin whiskers to chitosan films, improves chitosan tensile strength and the addition of α-chitin whiskers improved water resistance of the films.

Active and Smart Packaging

Active and smart/intelligent packaging terms are the most popular in food industry. The term '*active packaging*' is defined as *'packaging which provides containment and protection to the food in addition to which exhibits some active function to extend the shelf life of the food'* whereas '*smart packaging*' is meant '*to have the ability to sense an attribute of the product, change in the food atmosphere, etc*'. The incorporation of bioactive compounds such as antimicrobial compounds and antioxidants into food packaging materials has received considerable attention in recent years. Films with antimicrobial activity could help control the growth of pathogenic and spoilage microorganisms and thus extend the shelf-life of the food. An antimicrobial nanocomposite film is particularly desirable due to its acceptable structural integrity and barrier properties imparted by the nanocomposite matrix, and the antimicrobial properties contributed by the natural antimicrobial agents impregnated within. Materials in the nanoscale range have a higher surface-to-volume ratio when compared with their microscale counterparts. This allows nanomaterials to be able to attach more copies of biological molecules, which confers greater efficiency. Nanoscale materials have been investigated for antimicrobial activity so that they can be used as growth inhibitors, killing agents or antibiotic carriers (Vermeiren *et al*. 1999; Lagaron *et al*. 2005; Sinha and Bousmina 2005). The findings of several research investigations clearly demonstrated that the application of nanocomposites in food packaging helps to expand the use of edible and biodegradable films.

Active bionanocomposite films are developed by incorporating nanoparticles and bioactive molecules in the natural polymer matrix such as protein, starch, etc., with the addition of plasticizers like glycerol. They are formed by casting or by traditional plastic processing techniques, such as extrusion (Baldwin 1994; Park *et al*.1996). The active components may be antioxidants and antimicrobials. They may be natural or synthetic which exerts some activity on the shelf life extension of the food. With the incorporation of this, the film forming solution is thus prepared and casted in the regular way, dried and stored. Then it is used as the primary packaging material for the food (Figure 3).

Figure 3: Flow Chart for Preparation of Active Bionanocomposite Films



Source: Rhim and Ng 2007.

Several bionanocomposite films have been developed so far by incorporating different nanomaterials (Table 2) and bioactive ingredients and assessed their suitability for various foods against different food pathogens and spoilage bacteria. Dias *et al*. (2013) developed antimicrobial packaging incorporated with allyl isothiocyanate (AIT) and carbon nanotube (CNT), and this packaging was used for shredded cooked chicken meat inoculated with *Salmonella choleraesuis* and they found that diffusion of the AIT from the film into the chicken reduced the microbial contamination, controlled oxidation and reduced the colour changes and these packages were effective for 40 days of storage.

Table 2: Nanomaterials Employed in Development of Biodegradable Films

Inorganic	Organic (Edible)
Nano clays (layered silicates) • Montmorillonite (MMT)	Chitosan Chitin or chitosan nanostructures
Carbon nanotubes • Single-wall nanotube (SWNT) • Multiwall nanotubes (MWNT)	Cellulose • Cellulose nanoreinforcements (CNRs) • Cellulose nano-whiskers • Cellulose nanofibers (CNF)
Silica nanoparticles • Silicon dioxide nano particles	Starch • Starch nanocrystals (SNCs)

Source: Authors' compilation.

Tunc and Duman (2011) prepared Methyl cellulose (MC)/carvacrol (CRV)/montmorillonite (MMT) nanocomposite films prepared to obtain active antimicrobial packaging materials. CRV release from films was investigated at different temperatures for 30 days and the antimicrobial activities of films were tested against *Escherichia coli* (*E. coli*) and *Staphylococcus aureus* (*S. aureus*) and it was found that these organisms were completely inhibited on the nutrient broth/bacteriological agar medium when film samples contained 11.1 ± 0.2 mg CRV. These nanocomposite films on sausage reduced *E. coli* and *S. aureus* counts by 0.9 and 0.7 log cfu/mL, respectively as per their report.

In the study carried out by Alboofetileh *et al*. (2014), antibacterial effects of clove, coriander, caraway, marjoram, cinnamon, and cumin essential oils were studied against three important food pathogens, *Escherichia coli*, *Staphylococcus aureus*, and *Listeria monocytogenes (L. monocytogenes)* and among that three most potent essential oils were subsequently incorporated into alginate/clay nanocomposite films. The antibacterial effectiveness of the prepared films against *E. coli*, *S. aureus*, and *L. monocytogenes* was studied for 12 days and found that marjoram showing highest antimicrobial activity against all three strains.

Chitosan based nanocomposite film was prepared by Abdollahi *et al*. (2012) by adding montmorillonite (MMT) nanoclay and rosemary essential oil (REO) to improve its physical and mechanical properties of the film as well as antimicrobial and antioxidant behaviour. The results showed that incorporating MMT and REO into chitosan improves water gain, water vapour permeability, and solubility of the chitosan film by more than 50 per cent. It was also shown that the combined effect of clay and REO improves significantly the tensile strength and elongation of the film and antimicrobial properties.

Initiatives by Indian Government to Promote Research on Nanoscience and Technology

The Government of India has approved the launch of a Mission on Nano Science and Technology (Nano Mission) in May 2007 with an allocation of Rs. 10 billion. The Department of Science and Technology is identified as the nodal agency for implementing the Nano Mission. The objective is to promote and develop all aspects of nanoscience and nanotechnology which have the potential to benefit the country and is steered by a Nano Mission Council (NMC) under the Chairmanship of Professor C.N.R. Rao. Several universities have established centres for nanomaterials and nanotechnology to develop new products and processes.

Indian agriculture scientists have been focusing on nanotechnology for a wide range of applications in agriculture, veterinary, aquaculture, food science, medicines and drugs, etc. The initiation of Indian Council of Agricultural Research (ICAR) in this context is the formation of 'Nanoplatform', wherein different ICAR research institutes and State Agriculture Universities (SAU'S) join hands and put their facilities and efforts together to efficiently utilise the tools of nanotechnology for the advancements in agriculture and allied sciences.

Several researchers have been working on this bionanocomposite films for food packaging including edible bionanocomposites. The Central Institute of Fisheries Education (CIFE) has been working on fish gelatin based films and the Central Institute of Fisheries Technology (CIFT) has been working on chitosan based films and checking their efficiency on shelf-life extension of fish products. The institutes like Central Institute for Research on Cotton Technology (CIRCOT), Mumbai; Tamil Nadu Agricultural University (TNAU), Coimbatore; Central Potato Research Institute (CPRI), Shimla have established the facilities for production of nanocomposites from natural polymers.

Conclusion

This review clearly showed the vast potential of utilising biopolymers for food packaging. Though the natural polymer-based biodegradable packaging materials possess a wide range of advantages, they have not been widely used in the food packaging industry due to their inherent poor mechanical and barrier properties. With the advent of nanotechnology, several research studies have been undertaken to develop bionanocomposites by incorporating different types of nanomaterials. In spite of improvements achieved in respect of mechanical and barrier properties through nanocomposition technology, these technological advances are not translated into commercial products. However, the development of active and smart packaging materials with the additional benefits of food protection and food safety would certainly help to capture huge potential of food packaging segment. Further studies and efforts are required for commercial production of bionanocomposite films to realise the importance of food packaging in reducing the colossal wastage of food and food products without causing any environmental concerns.

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Asian Biotechnology and Development Review
Vol. 15 No.3, pp 67-79

Overview of Nanobiotechnology Public R&D System in India

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Abstract: Nanobiotechnology, as an area of application of nanotechnology in the domain of biotechnology, is poised to have a strong influence on the various facets of the biotechnology sector such as agricultural biotechnology, animal biotechnology, environment biotechnology or health biotechnology. Many countries have initiated various programmes/schemes to harness the potentialities that nanotechnology has to offer in the biotechnology sector. This article attempts to present an overview of the nanobiotechnology public R&D system in India and carry out its SWOT analysis.

Key words: Nanobiotechnology, public R&D, SWOT analysis

Introduction

Nanotechnology, by virtue of its definition, has been claimed as an enabling technology with multidisciplinary orientation and multi-sectoral applications ranging from electronics to ICT to agriculture to healthcare and so on. Nanobiotechnology presents itself as a promising field of convergence of two technologies, viz. nanotechnology and biotechnology. Basically, it is related to the application of nanotechnology in the domains of biotechnology. This significant convergence has various applications in the diverse areas such as agriculture, animal biotechnology, biofertilisers, biopesticides, crop management, environmental biotechnology, food biotechnology and medical/health biotechnology (Roco 2003; Salata 2004; Surendiren *et al.* 2009; Sastry *et al.* 2010; TERI 2010; Ramani *et al.* 2011; NISTADS 2012; Fakrudin *et al.* 2012; Sastry *et al.* 2013).

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Most of these applications of Nanobiotechnology can have a positive bearing on addressing major socio-economic and developmental issues that affect the Indian society and economy such as agricultural productivity enhancement; water treatment and remediation; disease diagnosis and screening; drug delivery systems; food processing and storage; health monitoring; vector and pest detection and control. However, for realising these potential applications, an intensive Research and Development (& Innovation) in this field is an imperative. This article attempts to track down the initiatives undertaken so far by the Indian government in promoting R&D (&I) in Nanobiotechnology and capture the strengths and weaknesses of the current endeavour.

Nanobiotechnology Public R&D System in India

India, along with, many other developed and developing countries, has been actively involved in leveraging the maximum potential benefits that can accrue from applying nanotechnology in various sectors since early 2000s. The plans and multiple initiatives started by the government since the beginning has played a major role in developing capacity building in terms of physical infrastructure, human resources and institutional framework for nanobiotechnology.

The immense potentialities of nanotechnology were realised by the Planning Commission way back in 1998, when in the Ninth Five-Year Plan (1998-2002) it was mentioned that national facilities and core groups were set up to promote research in frontier areas of S&T which included superconductivity, robotics, neurosciences and carbon and "nano materials". The Planning Commission supported a number of such R&D programmes under the basic research (GOI 1998). The Tenth Five Year Plan (2002-2007) identified various areas for mission mode programmes such as technology for bamboo products, drugs and pharmaceutical research, instrument development including development of machinery and equipment, seismology, nano science and technology. It also mentioned that "under the drugs and pharmaceuticals research programme, several new projects relating to the nutritional deficiency and related diseases – iron and protein deficiency, herbal drugs, new drug delivery systems, etc., – would be initiated and efforts will also be made to set up new national facilities for screening of anti-viral activity, combinatorial synthesis, high throughput screening, regulatory toxicology, clinical pharmacology, etc." (GOI 2002). The Eleventh Five-Year Plan (2007-2012) categorically mentioned that "Nanobiotechnology applications for drug, delivery, biosensors, microbial prospecting for novel compounds, genes, bio-energy and bio-fuels, bioremediation, and so on, are other important thrust areas." It went on to mention the bright future prospects of convergence of bio-nano-info technologies and of Nano-Bio-Information Technology-Cognitive (NBIC) convergence. It further mentioned that with the focus on translational and innovation activities in nanobiotechnology, the existing autonomous institutions would be remodeled, which would require expansion of the scope of the institutions by building centres of translation, innovations and services along with focused networking (GOI 2007). Recently, the Twelfth Five-Year (2012-17) Plan mentioned about connecting and augmenting existing competencies across institutions for bio-economy and social impact. The thrust has been placed on translational research connecting nano-science, chemical science and pharmaceutical science with clinical research for novel drug delivery, novel diagnostic and medical imaging, etc. It also mentioned about promoting new-generation biotech industries such as nano-bio industries (GOI 2012).

These Plan documents shed light on the vision that the government intends to pursue in the area of broader Science and Technology development in the country. Since quite early, it can be seen that the focus has been accorded to the development of nanotechnologies and their applications in various areas. Nanobiotechnology has been given a status of "thrust area". Accordingly, individual Ministries/Departments have initiated many schemes or programme to realise the vision expressed in the Plan Documents from time to time.

The pioneering role in the area of broader nanotechnology R&D in India has been steered by the Department of Science and Technology (DST). The DST launched special initiative to generate and support some end-to-end projects leading to tangible processes, products and technologies after realising the importance of nanomaterials and its far-reaching impact on technology. Special emphasis was laid on projects aimed at "solving important national problems like pure drinking water, alternative energy sources, energy conservation, etc., and value addition of materials" (DST 2001).

In 2001-2002, the DST set up an Expert Group on "Nanomaterials: Science and Devices". The Government identified the need to initiate a Nanomaterials Science and Technology Mission (NSTM) in the Tenth Five Year Plan (2002-07) after taking into consideration the developments in nanotechnology (DST 2002).

Subsequently, the National Nanoscience and Nanotechnology Initiative (NSTI) was launched in October 2001 under the aegis of the Department of Science and Technology (Ministry of Science). This initiative was started by the DST soon after the launch of the USA's National Nanotechnology Initiative (NNI) in 2000. The motive of launching the NSTI in 2001 was to create research infrastructure and promote basic research in nanoscience and nanotechnology. It focused on various issues relating to infrastructure development, basic research and application oriented programmes in nanomaterial including drugs/drug delivery/gene targeting and DNA chips. Nanotechnology was heralded as a revolutionary technology with applications in almost every aspect of life (DST 2004).

The Nano Science and Technology Mission (NSTM) was launched by DST in 2007 to foster, promote and develop all aspects of nanoscience and nanotechnology which have the potential to benefit the country. Basic Research Promotion under the NSTM mentioned about exploring the role of nanotechnology application in the fields of biotechnology, pharmaceutical industry and drug delivery among other focus areas (DST 2008).

However, in the case of nanobiotechnology, the major nodal agency that is involved in India is the Department of Biotechnology (DBT). It has been actively involved in promoting basic and applied research into the emerging area of nanobiotechnology R&D (&I) through various initiatives/ schemes since early 2000s.

In the period 2002-03, the Department of Biotechnology (DBT) set up a separate Task Force on nanobiotechnology to suggest priority areas for R&D in nanobiotechnology. This was the first effort to accord exclusive recognition to the role of nanotechnology in the field of biotechnology. The areas identified by the task force for R&D were: nanoparticles for diagnostic/ therapeutic use; bio-nano composites, biosynthesis of nanomaterials; and imaging/sensing of nanoparticles/bio-molecules (DBT 2004).

In the period around 2007, the DBT, keeping the importance of nanotechnology applications in biological sciences, initiated a Programme of nanobiotechnology (DBT 2008). Since then, this Programme has promoted basic R&D in the areas of: (a) nanotechnology for food/agriculture: weed utility, nanosensor for crop protection, pesticide delivery vehicles, nanocides, smart packaging, sensors for detection of pathogens and chemicals in food and crop, etc.; (b) nanotechnology for animal husbandry: biodegradable nanoparticles for drug delivery, etc.; (c) nanotechnology for environment management: biosysnthesis of nanoparticles, treatment of industrial effluent, waste management, etc.; (d) nanotechnology for healthcare/medicine/drug delivery: drug delivery system, disease diagnosis, cancer and TB therapy, scaffolds, medical devices, implants and imaging, etc.; and (e) nanotechnology in other allied areas: bioengineering, water filtration, toxicity assessments, etc.

Many projects were funded and implemented on these thematic areas of nanobiotechnology applications by the DBT in several of its autonomous institutions and other universities/institutes such as IISc and IITs (DBT 2007-2013). The autonomous institutions under the DBT, which are involved in R&D in nanobiotechnology, are as follows:

- National Institute of Immunology, New Delhi (NII): Research in nanobiotechnology includes the translational research in the area of vaccines and drug development. The research is focused on designing novel immunogens, anticancer agents and therapeutic inhibitors against pathogens of public health significance.
- National Centre for Cell Science, Pune (NCCS): The centre focuses on basic research in the nanobiotechnology areas of cell biology, cancer biology, molecular biology and tissue engineering that leads to enhancement in understanding the events at molecular level.
- Institute of Life Sciences, Bhubaneswar (ILS): Application of modern technologies such as nano-biotechnology is focused towards treating cancer.
- Rajiv Gandhi Centre for Biotechnology, Thiruvanthapuram (RGCB): Application of modern technologies such as nano-biotechnology is focused towards delivery systems, and understanding the fundamentals of cellular functions during disease.

- Translational Health Science and Technology Institute, Gurgaon (THSTI): THSTI integrates multidisciplinary scientific teams from the fields of medicine, science and technology for harnessing translational knowledge. The process is directed towards the production of biomedical innovations for use in various phases of health care. Niche Centers in THSTI are: Vaccine and Infectious Disease Research Center (VIDRC); Pediatric Biology Center (PBC); Center for Bio-design and Diagnostics (CBD); Policy Center for Biomedical Research (PCBR); Drug Discovery Research Center (DDRC); and Center for Human Microbial Ecology (CHME). Extramural Centers are: Clinical Development Services Agency (CDSA); and National Biodesign Alliance (NBA). The partnership Center is: Population Science Partnership Center (PSPC).
- National Agri-Food Biotechnology Institute, Mohali (NABI): Application of modern technologies such as nano-biotechnology is focused towards crops, food and nutrition science and research.

Initiatives to Promote Nanobiotechnology Entrepreneurship

Apart from promoting research in nanobiotechnology in these knowledge generation centres all across the country, the DBT has been actively involved in setting up of Biotech parks, incubators and biotech science clusters and launching various initiatives to promote biotechnology entrepreneurship and to facilitate innovation through the development of a biotechnology industrial cluster and create a skill pool of biotechnologists and entrepreneurs who have a strong foundation in research and innovation (DBT 2013) such as: Small Business Innovation Research Initiative (SBIRI); Biotechnology Industry Research Assistance Council (BIRAC); Biotechnology Industry Partnership Programme (BIPP); Biotechnology Ignition Grant (BIG); and Contract Research Scheme (CRS). Some of the prominent biotechnology parks and incubators are: Biotechnology Park, Lucknow (Uttar Pradesh); Biotechnology Park, Bangalore (Karnataka); Guwahati Biotech Park Technology Incubation Centre, Guwahati (Assam); and TIDCO Centre for Life Sciences (TICEL) Bio Park, Chennai (Tamil Nadu).

The idea of Biotech Science Cluster has been conceived recently by the DBT while realising that for the growth of biotechnology entrepreneurship, emphasis on innovation is critical. Accordingly, as a part of its biotech strategy, the DBT proposed creation of multi-institutional regional clusters at certain locations. The Department took an initiative during the Eleventh Plan to establish biocluster as per the recommendations of the National Biotech Strategy. Accordingly, Biotech Science Clusters have been established which include: NCR Biotech Science Cluster, Faridabad; Bangalore Biotech Science Cluster, Bangalore; and Mohali Biotech Science Cluster, Mohali (DBT 2013). Overall objective is to enable integrated growth of science, engineering, agriculture and medicine in a multidisciplinary environment. Some of the prominent Biotech Science Clusters are as follows[1]:

- NCR Biotech Science Cluster, Faridabad: THSTI forms a pivotal node in a broader cluster of institutes known as the NCR Biotech Science Cluster. Institutes in the cluster will specialise in translational research and related endeavours. It is an ambitious initiative that aims to create a unique institutional ecosystem for the conduct of truly multidisciplinary research for translation to targeted medical innovations for improvement of public health. The four founding institutions are, namely NII; Regional Centre for Biotechnology (RCB); THSTI; and the National Institute of Plant Genome Research (NIPGR).
- Bangalore Biotech Science Cluster: A distinctively different biotech science ecosystem has been evolved in Bangalore. This includes: National Centre for Biological Sciences, Stem Cell Science and Regenerative Medicine; and Centre for Cellular and Molecular Platforms. The focus of this cluster range from basic biology; bioengineering; creation and management of national mouse resource; translational research; entrepreneurship; manage and develop novel high end technologies for the biotech sciences; provide access and training on such technologies; and outreach programmes via international meetings, courses and workshop.
- Mohali Biotech Science Cluster: The institutes of Mohali Biotech Science Cluster are: National Agri-Food Biotechnology Institute; Centre for Agri-Food Bioprocessing; Indian Institute of Science Education and Research; Institute for Nano Science and Technology; and a Biotech Park. This cluster will provide organisational structure and governance aimed at synergising skills, facilities and resources for development of meta-structures to accelerate human resource

development in trans disciplinary areas in agri-food-health sector, for building strengths in innovations at the interface of different specialisations in science, engineering, technology development and management through sharing of resources and skills, related to agriculture, food and health.

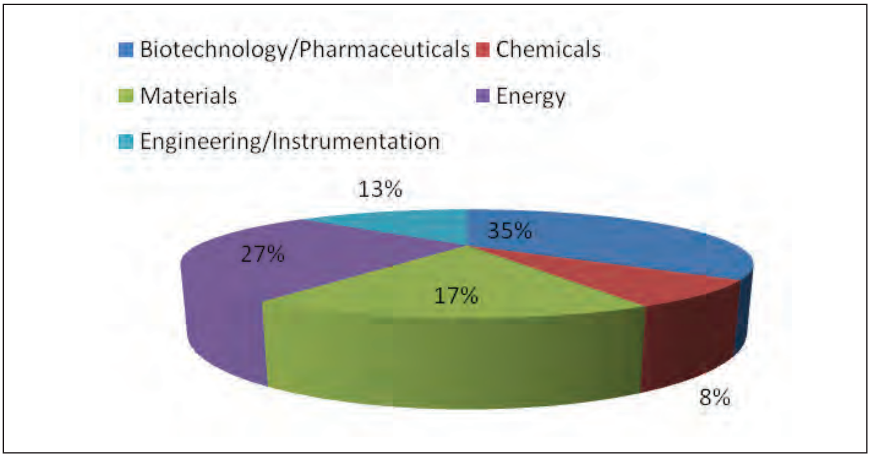
SWOT Analysis of the Present Nanobiotechnology Public R&D System in India

SWOT analysis stands for the analysis of strengths, weaknesses, opportunities and threats. Its application for analysing the present nanobiotechnology public R&D system will help in capturing the major areas of concerns.

Strengths

The strength in the present nanobiotechnology public R&D system in India is basically the strong foundational base that has been provided by the biotechnology sector, particularly by pharma/medicine sub-sector. Given the well-established medical biotechnology R&D platform, the integration of nanotechnology is very promising in areas such as drug delivery, disease diagnosis, cancer/TB/tumor treatment and implants. The various initiatives taken by the DBT to foster and nourish nanobiotechnology-based industrial development in the country is a right step towards creating a sound eco-system for R&D and innovation.

Figure 1: Major Sectoral Applications of Nanotechnology

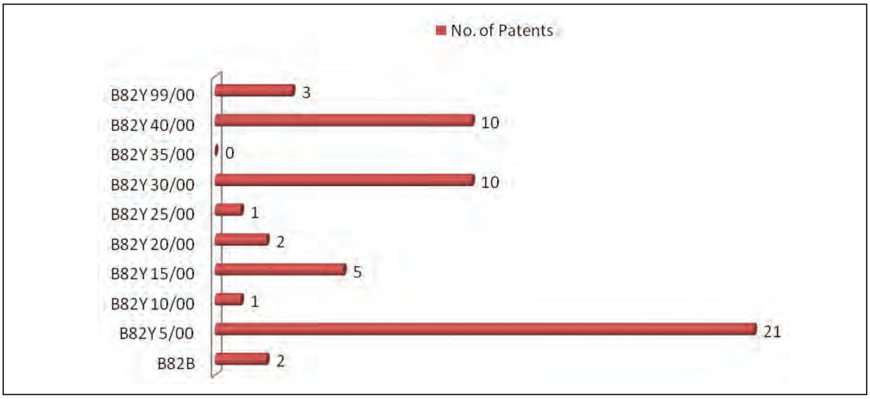


Source: Kumar (2013).

On analysing all the granted patents in "nano" by the United States Patent and Trademark Office (USPTO) to Indian actors, it is found that they have been most active in filing patents in Biotechnology/Pharmaceuticals (35 per cent) followed by Energy sector (27 per cent) (see Figure 1).

The similar evidence is seen when the analysis was carried out on the Indian patents applications in exclusive Nanotechnology B82 Class at USPTO. B82Y 5/00 which belongs to nano-biotechnology or nano-medicine has highest share (Figure 2).

Figure 2: Applied Indian Patents in B82 "Nanotechnology" Class at USPTO in the Period 2000-2012



Source: Kumar (2013).

The preceding analysis shows that Indian actors are also keen in protecting their innovation in the field of nanobiotechnology through IPRs and patents at global level too, which is an encouraging scenario. (Complete list of International Patent Classification on Nanotechnology is given in Box 1.)

Weaknesses

Weakness in the present nanobiotechnology public R&D system in India can be found in the sub-sectoral R&D focus of the overall nanobiotechnology R&D. Though the DBT has been keen in promoting R&D in the application of nanobiotechnology in the area of agriculture, medicine and environment; there has not been substantive research output yet in the area of agriculture and environment management. The issue of agricultural productivity enhancement, better crop and pest management is very crucial for India and given the promise that nanobiotechnology can play in this area, it would be very pertinent for the government to aggressively promote nanobiotechnology R&D in this area.

Box 1: International Patent Classification on Nanotechnology

B82	Nanotechnology
B82B 1/00	Nano-structures formed by manipulation of individual atoms or molecules, or limited collections of atoms or molecules as discrete units
B82B 3/00	Manufacture or treatment of nano-structures by manipulation of individual atoms or molecules, or limited collections of atoms or molecules as discrete units
B82Y 5/00	Nano-biotechnology or nano-medicine, e.g. protein engineering or drug delivery
B82Y 10/00	Nano-technology for information processing, storage or transmission, e.g. quantum computing or single electron logic
B82Y 15/00	Nano-technology for interacting, sensing or actuating, e.g. quantum dots as markers in protein assays or molecular motors
B82Y 20/00	Nano-optics, e.g. quantum optics or photonic crystals
B82Y 25/00	Nano-magnetism, e.g. magnetoimpedance, anisotropic magnetoresistance, giant magnetoresistance or tunneling magnetoresistance
B82Y 30/00	Nano-technology for materials or surface science, e.g. nano-composites
B82Y 35/00	Methods or apparatus for measurement or analysis of nano-structures
B82Y 40/00	Manufacture or treatment of nano-structures
B82Y 99/00	Subject matter not provided for in other groups of this subclass

Opportunities

Opportunities that come in front of the present scenario are those of utilising the benefits that can accrue from the nanotechnological applications in the domain of biotechnology to address many pressing societal challenges in an effective way such as drinking water, sanitation, food, waste management, healthcare, and pollution, along with leveraging its potentialities for economic growth in the form of promoting nano-bio industries for innovative products in healthcare/pharma sub-sector. Nanobiotechnology provides an opportunity for India to register a strong global presence in the area of medicine and healthcare.

Threats

The areas of concern which can be perceived as a threat include the lagged or inadequate focus on the risk and safety assessment issues arising out from the nanobiotechnology applications. The concrete guidelines for ensuring safety of researchers in the labs and workers in the industries are yet to come out. The proper mechanisms to ensure consumer protection, awareness and participation through labelling and stakeholder consultations are yet to develop. The standardisation of nano-materials needs to be completed soon. In absence of which proper monitoring and assessment will not be feasible. This might have an adverse impact on product development and trade. With the emergence of nano-bio-info or nano-bio-info-cognitive convergence in the future, this is likely to have challenges in terms of which department/ministry will be the nodal agency to look after the regulations in this specific case.

Conclusion

Nanotechnology has found significant applications in diverse areas such as agriculture, medicine, electronics, environment, cosmetics, construction, textiles, etc. However, its applications in the wider field of biotechnology are much more encompassing and significant. The wide array of nanobiotechnological interventions in fields such as agriculture, medical, animal, environment hold greater significance for countries like India. In this context, the pioneering role played by the government bodies/public R&D in promoting this stream of technology is quite commendable.

However, the SWOT analysis points out that there are certain issues that need to be taken care of for building or shaping a robust nanobiotechnology public R&D system in the country. The strength of well-established pharma biotech sector in the country must be used for coming out with effective and innovative healthcare systems soon. The private players can play a significant role in this endeavour, as major pharma companies in India are in private domain. The public R&D institutions in other areas should also be concentrating on nanobiotechnological application in the fields of agriculture and environment management. While engaging in these activities, it would be pertinent to have in place a proper risk assessment framework so that any unintended or harmful consequences could be handled in a timely and proper manner. Integrating such a framework in the R&D system architecture is an imperative. Also the efforts towards standardisation will go a long way in protecting consumers and trade interests.

Endnote

[1] dbtindia.nic.in/docs/Biotech_Science_Cluster.pdf

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Asian Biotechnology and Development Review
Vol. 15 No.3, pp 81-101

'Moving Forward Responsibly[1]': From Agribiotechnology to Agrinanotechnology in India

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Abstract: The agribiotechnology debates in India over the last decade have set precedents for reflecting on the changing relationship between science and society. This article tries to engage with these lessons in order to stress the need to assimilate them while imagining new technological interventions such as nanotechnology for agriculture and their governance. While searching for an appropriate governance mechanism, the artilce opens up the parallel international debate on 'Responsible Innovation' (RI) in the context of emerging technologies, for scrutiny in the Indian context. In doing so, the article highlights the neglected power dynamics in the overall debates on responsible innovation and proposes a 'beam-balance' metaphor to engage with the idea of 'Responsible Innovation' in order to take the inequalities and alternative perspectives into account.

Key words: Agribiotechnology, responsible innovation, nanotechnology, science and society

Introduction

Nanotechnology is projected to be a revolutionary technology in the near future in the field of renewable energy, healthcare, military and the environment (Sastry *et al.* 2010; Cozzens *et al.* 2013; Ramani *et al.* 2010). In the agro-food sector, applications of nanotechnology are proposed to provide answers to major challenges of food security and malnutrition making it a special focus for developing countries (Sastry *et al.* 2011; Cozzens *et al.* 2013).

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The author is thankful to Prof. Pranav Desai for his constant support during the research work; andAviram Sharma and Vidya Subramanian for extensive comments on previous drafts. Parts of this article were presented in various conferences such as Second Responsible Innovation Conference at Den Haag, December 2012; Globelics Academy, Tempere, May 2013; and S.Net Conference, Boston, October 2013. The article has greatly benefitted from discussions with various international scholars at these platforms.

With so much to be offered by these potential technologies words of caution are being issued from various sections of society to ‘move forward responsibly’ (Kuzma 2007). These range from radical approaches such as moratoria on research and commercialisation of nanotechnology (ETC group 2002) to approaches advocating more research on ethical, social, and environmental aspects of the technology. Responsibility thus is being variously defined depending on the actors, networks and contexts. Among many others, one of the main features of being responsible is learning lessons from the past while developing an effective oversight mechanism for the future (Kuzma 2007; Kearnes *et al.* 2006). Taking the case of nanotechnology in India, this article explores the aspect of responsibility by reflecting upon the lessons learned from the agribiotechnology situation in order to inform the debates around democratic governance of nanotechnology (Beumer and Bhattacharya 2013; Choudhary 2006).

After the strategic promotion by the governments through mission mode programmes for 10 years, nanotechnology is roughly at the same stage of development as was biotechnology in the early 1980s. The basic capacity building goals (both in infrastructure and human resource) seem more or less achieved. Institutes in the form of centre of excellence of nanoscience and nanotechnology in various parts of the country provide the basic scientific pool to carry forward rigorous R&D in the field, the patent and publication bars are on the rise, and international collaborations and public-private partnerships are intensifying (Beumer and Bhattacharya 2013; Bhattacharya *et al.* 2012, Sastry *et al.* 2010; Cozzens *et al.* 2013; Ramani *et al.* 2010). Before taking the next step in this direction by institutionalisation of nanotechnology specific regulatory and governance systems, it might be useful to do a detour in the agribiotechnology experience of the last two decades to learn the lessons it offers for the efficient governance of nanotechnology in India.

In the international context, the comparison between agri-biotechnology and nanotechnology and the lessons which might be learned from it has been done by various authors (Levidow 1998; Kearnes *et al.* 2006; Einsiedel and Goldenberg 2004). Rather than doing a product-based comparison between the two technologies (which is difficult provided the absence of any product in the agrinanotechnology in India), this article tries to shed some light on the discursive and ideational space in which nanotechnology and its products will be seen in the agri-food systems. As a possible way forward, this article, relating to the messages from the agribiotechnology situation, opens up the parallel international debate on ‘Responsible Innovation’ (RI) in the context of emerging technologies, for scrutiny in the Indian context. In doing so, the article highlights the neglected power dynamics in the overall debates on responsible innovation and proposes a ‘beam-balance’ metaphor to engage with the idea of ‘Responsible Innovation’ in order to take the developing countries’ perspectives into account.

This article relies on an in-depth review of secondary literature. Along with that reports and website information available in the public domain for agribiotechnology, nanotechnology and responsible innovation were analysed in a systematic manner. The empirical evidences are drawn from extensive field-work (carried out between April-June 2011) which included interviews with various stakeholders (scientists, farmers, consumers, seed companies, NGOs and media) in the agribiotechnology situation in India. Various international seminars and workshops attended by the author were used as another site of analysis to study the growing debates on Responsible Innovation.

From Agribiotechnology to Agrinanotechnology: What Can be Learned?

Sastry *et al*. (2013) in their assessment of the emerging trends in nanotechnology in agri-food sector advocate the ‘evolution of a participatory, dynamic and responsive nanotechnology policy and strategy for Indian agriculture and food systems’ if the technology is envisioned to ‘benefit the agrarian society’ (p.839). Does the premise of this policy advice ask to engage in the questions of the need to promote participation in the fields of expert oriented technoscience? What is meant by ‘participation’, ‘dynamic’ and ‘responsive’ in the socio-technical landscape of agri-food systems in India? As argued previously by scholars of Science and Technology Studies (STS), nanotechnology in agri-food, however, is not just a matter of tinkering with the ‘problems’ of particular foods, crops or animals in order to ‘improve’ them (Jasanoff 2007). It involves reshaping an entire network of production and consumption that addresses two most fundamental human needs, i.e. food and livelihood. The speed with which new technology is emerging is parallel to the speed with which old technology is getting obsolete, giving shock waves to the socio-technical systems. The negative consequences of Green Revolution in the form of loss of biodiversity, salination of soil, assimilation of pesticides in the food chain and deskilling of farmers indicate the need for a careful assessment of technological interventions in relation to the social and environmental systems (Shiva *et al.* 1999; Stone 2007).

For a country like India, where some 700 million people rely on the agriculture in one way or another, the central question facing any technology choice (such as nanotechnology) is the future of food and farming and its effects on rural livelihoods (Scoones 2006; Pimbert and Wakeford 2002). Although science and technology innovation in the contemporary world transcend the national boundaries and join into a global system, the consumption and governance architecture still lingers to the national contexts (Jasanoff 2007). The inability of emerging technologies to take account of this complex and interconnected global-local context keeps them from engaging with the broader socio-cultural milieu in which they are supposed to operate. The situation of ‘policy-logjam’ (Chaturvedi and Srinivas 2013) in the case of agribiotechnology in India asserts a need for re-thinking the existing models of governance and the instruments of trust and legitimacy in the science-society relationships (Gupta 2011). In this regard, the next section focuses on what constitutes the agri-food system in India? Who are the actors connected with what networks? How have previous technologies such as Green Revolution and agribiotechnology sensitised and shaped the discursive spaces in which various aspects such as food safety and security, product promotion and media hype, intellectual property and indigenous knowledge (Desai 2003), and role of multinational are visualised (Jasanoff 2007)? And how can these aspects inform and shape the debates related to governance of nanotechnology?

Of Hopes, Hype and Imaginaries

Expectations play an important performative role in science and technology innovations (Te Kulve *et al.* 2013; Borup *et al.* 2006; Hedgecoe and Martin

2003). The possible forms in which expectations perform include hopes, hype, fears, promises and concerns framed with optimistic or pessimistic valuations and woven into vision and imaginaries. While visions are goal oriented optimistic plans about a technology, imaginaries are much broader and multi-faceted. Socio-technical imaginaries, as argued by Jasanoff and Kim (2009) are, 'imagined forms of social life and social reflected in design and fulfillment of innovative scientific and/or technological projects.' They aim to highlight how different democratic political cultures frame the goals, risks, and benefits of technological innovation. Thus, the field of nanotechnology is constantly being visualised through the aid of visions which are descriptive of the future to be aimed for, as well as prescriptive of how that ought to be attained. Starting from the famous Feynman slogan of 'there is plenty of room at the bottom', there has been an ever increasing rush to visualise what counts as nanotechnology and the properties associated to that scale and what counts as mere fiction. The famous Drexler-Smalley debate (Selin 2006) demonstrates the performative power of visions to associate legitimacy to certain claims of reality rather than others. In that sense nanotechnology is not simply an emerging field of scientific research and experimentation, but also a space constituted through the deployment of a range of discursive repertoires of promise and expectation (Grove-White *et al.* 2000, Kearnes *et al.* 2006). Thus, in the early stages of technology development filled with high level of uncertainty and contestation, the widely shared expectations or imaginaries (those that enroll multiple stakeholders by employing tools such as investment, publicity and public concerns) have greater effects on influencing the co-production of science and social order (Jasanoff 2005).

The visions such as 'windows of opportunity to catch up in the global competitiveness' (Rao 2008; Mashalker 2008), 'pro-poor technologies' (referred in Ramani *et al.* 2010), 'second Green Revolution' (Sastry *et al.* 2011) are premised on a tacit, normative understanding of societal progress through technological advancements. A flashback at the formative years of biotechnology in India reminds us of many similar imaginaries being projected by governments, multinationals, and media (Scoones 2006). As a result of the insulation of these imaginaries from changing social context and debates, the innovation resulting from them lacked responsibility and accountability on behalf of those who were going to be affected resulting in what turned out to be the agribiotechnology controversy. Cozzens *et al.* (2013) argue that most of the research carried out with regard to innovation in countries like India and China has been framed in terms of their international competitiveness rather than a contribution to solving internal country specific problems of poverty, malnutrition and lack of health services. They argue (Cozzens *et al.* 2013) that 'what is generally assumed is that going up in international competition will automatically contribute to the solution of such problems', but as it is observed through their study, in the present context the innovation dynamics is skewed more towards global innovation networks where it is very likely that the benefits from such activities might concentrate among the elites in the absence of a focus on local situations (Cozzens *et al.* 2013).

The visions of second Green Revolution are being repetitively transposed to the imaginary of nanotechnology in India (Sastry *et al*. 2011). Generally assembled as the food security problem the narrative of 'crises and plenty' along with the technocratic developmental ideals prevail in these images. These narratives, lacking any commitment of care for the changing socio-cultural context and asymmetries created by earlier technologies, were severely criticised in the agribiotechnology situation (Sharma 2003).

The visions and imaginations fuel the advancement of scientific innovations (Kearnes *et al.* 2006). What could be learned from the agribiotechnology situation in India is the fact that while performing this historical transposition of visions, sometimes the socio-cultural context gets neglected leading to transformation of an imaginary into mere rhetoric or unsubstantiated hype. For example, while discussing about the extension of the imaginary of Green Revolution to agribiotechnology in India, Visvanathan (2003) argues that 'while making the transition from the Green Revolution to the agribiotechnology revolution, it should be emphasised that the line demarcating the two is not a border but a threshold. The old categories of nation-state-science-development, which constituted the 'aura' of the Green Revolution in the 1960s, were now engulfed by new concepts, necessitated both by the centrifugal forces of the decades of struggle by the grassroots groups and the centripetal forces of the emerging demands of globalisation'. Since technology and society are interconnected and choosing a particular technology implies the choice of society (Scoones 2006; Jasanoff and Kim 2009), the transposition of past imaginaries to a future socio-technical space needs to be done in a reflexive, grounded, symmetrical and context specific manner. This implies that the criteria of technological choice which rely only on cost and returns, commercial viability, export potential and contribution to GDP are insufficient. The socio-technical imaginary needs to be envisioned on a premise of sensitivity to broader understandings of risks, uncertainty, ethics and social structure and accommodative of alternatives. The agribiotechnology story also advocates for the opening up of the visions and imaginaries for public examination in order to increase the robustness of these visions (Kearnes *et al.* 2006; Jasanoff 2005; Scoones 2006).

Of Risks and Associated Responsibilities

In India, the system of regulation for agribiotechnology is based on the risk-biosafety model, which draws from the environmental regulation brought in place after the Bhopal Gas Tragedy (Damodaran 2005). This technocratic style of regulation operates within the carefully constructed boundaries between science and values, biosafety and politics (Scoones 2006). As the sole purpose of regulation became managing scientifically definable risks[2], the risks become the only point of entry for debates around regulation of agribiotechnology in India (Scoones 2006). By sanitising 'risk' from wider socio-economic impacts on the basis of scientific definitions (Chaturvedi *et al.* 2012), the understanding of innovation as a complex process (with intended and unintended consequences) has been narrowed. In this regard, Mehta (2008) argues that 'by treating risk as a tradable commodity, or even as a future market instrument, the world has decontextualised risk and has bracketed off several of the nonmonetary and nonscientific dimensions associated with technologies that produce risk. This process of decontextualisation connects squarely the assessment and management of risks to an innovation agenda where the traditional role of the nation-state as guardian of the public good has been transformed into that of an enabler of technologically induced economic growth'(Mehta 2008).

It was widely recognised through many studies worldwide[3] that the attitudes and skepticism of the people were not driven by 'risk' in the scientifically understood sense of hazard and probabilities, but were much more about institutional and cultural (ir)responsibilities (Parr 2005). In the traditional manner of risk regulation the practices, by which legal or moral responsibilities are established, typically locate responsibility as a condition that obtains after the boundary between harm and harmlessness is crossed. If certain risks were not predicted at the time of acting due to the state of knowledge at that time, the agent who committed the act can escape being held responsible for the unforeseen effects (Pellizzoni 2004 in Groves 2009). In a condition of radical indeterminateness (Wynne 2007) that derives from both the temporality of human existence and its embeddedness in complex socio-technical systems (Groves 2009), this tends to obscure the judgements of liability. Consequentialist models of responsibility like the above, in which the consequences of actions are judged in aftermaths, are deeply problematic for innovation as a future-oriented highly uncertain activity (Grinbaum and Groves 2013 as cited in Owen *et al.* 2013).

The precautionary principles in risk discourses are generally employed to remediate this situation. Current precautionary approaches to technological innovation operate as an extension of formal approaches to risk analysis. Precautionary measures are viewed as temporary fixes, which can be removed once a higher degree of scientific certainty about the absence of specific risks has been attained. Basing responsibility of action on knowledge of what has happened in the past and what is happening in the present is simply not sufficient, given the current world scenarios of high degree of complexities in science-society relationships. As pointed out by various authors, risk is only one dimension of the unintended consequences of a technology on a spatio-temporal scale. The other parameters, namely uncertainty, ignorance, and ambiguity, generally go unaccounted through the existing methods of risk analysis and management (Stirling 2007; Wynne 2007). Precautionary approaches take an externalist position where technology is viewed as a means to certain ends (Dupuy 2007). These approaches do not touch on the economic and wider social imperatives that condition how technologies develop, and nor do they take seriously the view that uncertainty is an inevitable product of technological innovation, rather than a temporary obstacle to it (Dupuy 2007).

In Indian agribiotechnology scenario, the credibility and scope of the regulatory system was challenged at three levels: the science, facts and data of risk assessment (Sahai 2004; Bhargava 2002); the political, social and moral questions about the nature of the technology (Sahai 2004; Sharma 2003; Shiva *et al.* 1999); and use of experts in the process of decision making on the grounds of transparency and inclusiveness (Chaturvedi and Srinivas 2013; Sahai 2009). This serves to deliver the essential lessons to broaden the meaning and scope of risk beyond the scientific definitions to accommodate the uncertainties and the unknowns. Risk assessment as a scientific form of appraisal needs to be associated with a broader discussion of public values of technology and its inherent normative aims (Kearnes *et al.* 2006).

The Science-Society Relationship

In India, the relationship between science and society is at the crossroads. The indeterminacy of the state actors to address issues of legitimacy concerned with science and expertise in the controversies surrounding Bt cotton, Bt brinjal and BRAI bill supports this claim (Pandey 2013; Gupta 2011). Despite being in a situation of constant flux, the dominant understanding of the science-society relationship, in framing nanotechnology initiatives and missions still seem to stem from the 'deficit-model' where the 'public' needs to be informed (Nanomission 2007). The 'public' in the official accounts of technology in India is often constructed as 'innocent', 'unaware' and 'uninformed' mass of people whose concerns arise as a cumulative effect of confusion due to lack of information and sensitisation by NGOs and media. Generalised projections, such as these, may carry detrimental implications for the science-society relations for two reasons. On one hand, these accounts try to misrepresent the capacity of NGOs and media as strong alliance and uniform entities who can go beyond the state power to influence the public (Kearnes *et al.* 2006; Jasanoff and Kim 2013). On the other hand, these generalisations disregard the agency of the people who are heterogeneous in their values, beliefs and approaches towards science and its applications and are capable of providing unbiased opinions about their understanding of a technology in their socio-cultural context (Wynne 2007).

While the Bt cotton controversies highlighted the unease in the country towards expert based decision making, contestations over Bt brinjal and BRAI bill showed how the mobilisation of material and ideational power occurred towards seeking a legitimacy for these decisions (Fuchs and Glaab 2011 in Gupta 2011). The agribiotechnology experience draws attention towards the need for public engagement platforms in the country which could act as a connection between the state machinery and citizen in order to account for the trust, legitimacy and robustness of scientific decisions. A culture of efficient Technology Assessment (TA) and Science, Technology and Society (STS) studies well integrated to the scientific research system and policy making can be a good start in this direction.

Agribiotechnology, as evident from the above discussion, emerged at the global platform in the network of relations where the 'old' politics of modernity (Jasanoff 2005), characterised by centralisation, singular rationality and objectivity as its core values, was confronted and often replaced by a 'new' politics of plurality, localism and constant thrust of uncertainty (Jasanoff 2005). Along with this, agribiotechnology emerged in a situation where (in the knowledge societies where knowledge is the commodity and knowledgeable individuals are the assets) nation-states and national systems of innovation are losing their hold. With the global transfer of scientific knowledge and technical skills, rise of transnational organisations and multinational corporations, and social movements enabled by increased communication channels, there is a constant pressure on various national and international agencies to rethink the models of democratic governance of technology (Jasanoff 2005). As a response, responsible innovation and the discourses surrounding it could be seen as a possible fertile ground to think about a new governance paradigm for emerging technologies.

The next section tries to examine the emerging, international discourse on responsible innovation which is running parallel to the debates on nanotechnology. The following section firstly engages with the issues of how responsible innovation is being defined in various national and international forums, by whom and with what implications. Then it tries to look critically at what is being missed out in this process. Next, the section reflects upon how some of these missed aspects could be taken into account while talking about innovations in a responsible manner.

Looking Forward Reflexively: Responsible Research and Innovation

The term 'Responsible Innovation' (RI) is gaining a lot of prominence in the European Union policy circles under the prospective EU Framework Programme for Research and Innovation "Horizon 2020" (Von Schomberg 2013). In the EU member states, there are also various initiatives supporting RI, notably under schemes of national research council in the United

Kingdom, Norway, and the Netherlands. In the USA the discussions on RI is gaining importance under the heading of Responsible Innovation and Responsible Governance (RI-RG), which is part of the National Nanotechnology Initiative (Roco *et al.* 2011). It could be regarded as the descendants of earlier discussions about research integrity and the ethical, legal and social implications of research (ELSI) in relation to the Human Genome Project (Guston and Sarewitz 2002). RI can also be associated to the visions for collaborations between social, natural and physical scientists that address the wider dimensions of science and innovation as is evident, for example, within the 5th and 6th EU Framework Programmes and their calls for socio-technical integration and greater public engagement with science and technology (Mejlgaard *et al.* 2012). Other roots include integrated approaches such as technology assessment in its various forms (Schot and Rip 1996; Guston and Sarewitz 2002) and anticipatory governance (Karinen and Guston 2010; Guston 2013).

The lessons learned from the biotechnology situation all over the world form the core of almost all discussions about Responsible Innovation (Owen *et al.* 2013; Schot and Rip 1996; Guston and Sarewitz 2002). Innovation in technology is inevitable and people's freedom to innovate is highly valuable and critical to humanity (Moore 2008). At the same time, the technocratic and linear understanding of innovation does not hold any ground in the present situation. It has been recognised, more specifically in this context, that there are often long time lags between the development and diffusion of novel innovations, understanding of their wider impacts and associated risks (on health, environment, and society), and subsequent regulation (as a key form of governance). As a response to the understanding of regulatory, ethical and societal aspects of innovations lagging behind their developments and giving rise to unforeseen consequences (Mnyusiwalla *et al.* 2003), Responsible Innovation advocates that 'right from the start, research, development and design [can] incorporate relevant ethical and societal aspects' so that 'technological and scientific advances become properly embedded in society' (NWO 2012).

Putting 'responsible' in front of innovation does not mean that till now all innovation has been 'irresponsible' as some authors have argued (Blok 2013). Rather, it argues that the values which 'innovation' has embodied till now need to change in the contemporary global context (Jonas 1984; Adam and Groves 2011; Grinbaum and Groves 2013; Owen *et al.* 2013). According to a prominent group of researchers working to develop a framework for Responsible Innovation in the UK and the USA, 'Responsible Innovation is a collective commitment of care for the future through responsive stewardship of science and innovation in the present (Owen *et al.* 2013)'. Rather than relying on minimising risk and avoiding harms this approach seeks to focus on positive aspects by cultivating a virtue of care (Randles *et al.* 2011). The future, as the horizon of care, cannot be identified as the open space beyond the present or as entirely empty (Adam and Groves 2007). The future is constantly made through the discourses, acts and aspirations of the present. Decisions taken in the present constrain the degree of freedom of the future. Thus the visions, hopes, hype and imaginaries of the future need to be embedded in the present through a commitment of care. The focus on care as dimension of responsibility (which is value- and not rule-based) allows for discussion concerning purposes of innovation and accommodates uncertainty (Jonas 1984; Pellizzoni 2004; Owen *et al.* 2013) which was not possible in earlier risk-based models of governance. In this regard, Responsible Innovation may serve the purpose of developing (through institutions, habits and practices) a reflexive capacity in the society to constantly engage with different aspects of emerging technologies at various stages of their development (Guston 2013).

Von Schomberg (2013) envisions Responsible Research and Innovation as a "transparent and interactive process by which societal actors and innovators become mutually responsive to each other with a view on the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products".

New and Emerging Science and Technology (NEST) can be characterised by an increasing trend towards the convergence of two or more disciplines in sciences. As a field of study, Responsible Innovation can be viewed as the convergence of various disciplines of social sciences to ensure a 'better science for a better society' (Owen *et al.* 2013). Scholars from science, technology and innovation policy studies have urged for critical reflexivity while studying the dynamics of innovation (Morlacchi and Martin 2009). Grunwald (2011) argues for the essentially interdisciplinary nature of Responsible Innovation drawing insights from technology assessment, technology governance, Science, Technology and Society (STS) studies, Science Technology and Innovation (STI) studies and applied ethics (Grunwald 2011).

Many new approaches, such as midstream modulation, which emphasise on a multidisciplinary interaction of the social scientists with scientist in laboratory settings to reflect on various aspects of their research results, are being brought to focus in this context (Fisher *et al.* 2006; McGregor *et al.* 2009). Another leading example is given by the Engineering and Physical Sciences Research Council (the largest public funder of basic innovation research in the United Kingdom) who, for the first time, asked applicants to submit a risk register identifying the wider potential impacts and associated risks (environment, health, societal, and ethical) of their proposed research (Owen and Goldberg 2010). According to Owen and Goldberg (2010), 'The aim was to underpin high-adventure creativity with responsibility at an early stage and to embed anticipatory and participatory approaches in an operational context as part of a major research council's funding activity'. Reflexivity is required not only from scientists and research funding agencies but also from social scientists, NGOs, mass media and the public. For the social scientists, it is a novel opportunity to become an actor in these changes and to provide insights that are simultaneous with scientific, technological, and social changes and which were often not fully recognised in the biotechnology debate (Macnaghten *et al.* 2005).

Responsible Innovation, argues Stirling (2012), is a 'double-edged sword'.[4] Still in the experimental phase of its development (Davis and Horst 2013) the idea has the potential to get molded in various shapes. Qualities such as broader outlook, interpretive flexibility, reflexivity, and deliberation may turn detrimental if not used with due consideration of the context. In this regard, a number of scholars are already engaged in looking at the concept critically in order to enhance its reflexivity (Davis and Horst 2013; Blok 2013; Randles *et al.* 2012). The broader outlook and interpretive flexibility of the term suffers from the dangers of being admissive of only grand challenges which cannot be pinned down to any single solution (Blok 2013) and of being a rarified debate with nothing specific to offer (Davis and Horst 2013). As recognised from many criticisms of the linear model of innovation, in reality innovation is complex, messy and collective in nature often intertwined across cultures and continents (Bessant in press as cited in Owen *et al.* 2013). Innovation is generally a result of this complex interaction of institutions, organisations, research and development units, think-tanks, planning departments and public administration rather than the Schumpeterian entrepreneur (Akrich *et al.* 2002). As a consequence of this complex innovation ecosystem, irresponsibility is complex and intertwined rather than being the sole action of an individual scientist or innovator. RI needs to be operationalised in such an ecosystem (Owen *et al.* 2012). In such a situation, as argued by Hankins (2013), 'is it possible to pre-package 'ethics and responsibility' in blanket fashion? Is it a skill in professional deliberation that needs to be instilled?' Responsible innovation thus needs to be constantly self-reflexive by having greater awareness of the histories, cultures, and normative frameworks that have led and regularly lead to the ethical conundrums of an 'irresponsible' innovation (Hankins 2013).

While talking about responsible innovation as a lens to look forward in the socio-technical space a debate, which is generally not much explored, is the power dynamics inherent in the innovation systems emerging at the global level (Randles *et al.* 2012; Desai 2009). The prominent discussions on Responsible Innovation (for example, Randles *et al.* 2012; Grunwald 2011;Von Schomberg 2013; Owen *et al.* 2012, 13; Roco *et al.* 2011) rely on an interplay of the relationship between two broader categories. They are:

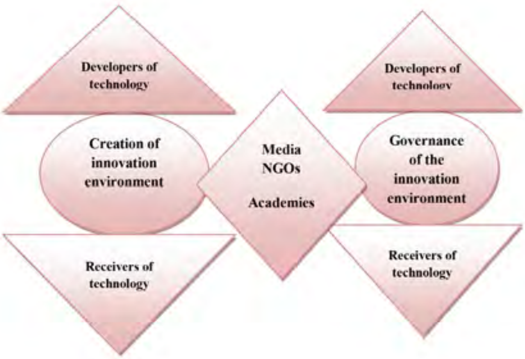
- The creation of an innovation environment, and
- Governance of the innovation environment.

The creation of an innovation environment ensures to facilitate technology development by capacity building, international collaborations, and promoting research projects. The governance of innovation environment considers ethical, social and technology assessment aspects of technology.

A neglect of the power dynamics playing between promotion of innovations and governance of innovations at the global level may reduce the potency of the debates on responsible innovation to the banality of the business-as-usual. This article proposes that the power dynamics of the global innovation network can be captured if Responsible Innovation is understood through the metaphor of the 'traditional weighing balance' (hand operated, with two pans attached to a beam). The metaphor of beam-balance, if internalised in the understanding of Responsible Innovation, might help in increasing the sensitivity towards the skewed power dynamics inherent in global innovation and their global governance. The metaphor, as applied to Responsible Innovation, operationalises in the following fashion. Firstly, the pans symbolise the creation of innovation environment and governance of the innovation environment as two aspects of Responsible Innovation, a balance between the two is sought after for a sustainable society. As is evident from the bibliometric analysis of the nanoresearch in India in the agri-food sector (Sastry *et al.* 2013), there is relatively a very little focus on the research on evaluation tools of possible risks of nanotechnology in this field. Although there were significant number of publications (24 per cent) on risks aspects, the patent data base did not yield any technologies for risk assessment. In order to address uncertainty related to the potential risks of nanotechnology, it becomes necessary to develop an approach to the governance of innovation dynamics in parallel to the promotion of innovation dynamics through strategic investments in both fields.

Secondly, to understand the aims and purposes the framework might serve, it becomes important to understand 'who' is holding that balance. Actors with different institutional interests might use the framework of responsible innovation for different purposes such as instrumental, legitimatory or justificatory (Stirling 2007). Third, in order to understand the 'ends' to which the concept can attend, the context in which the weighing balance (Responsible Innovation) is being used becomes crucial. This reflects upon its capacity to attend to the needs of that particular context. For example, for an antique shop in a developed country the traditional weighing balance may serve as a decorative item, whereas for a poor shopkeeper in a developing country it is the source of his/her daily livelihood. This dimension of the metaphor is important as it reflects on the international frameworks, which are developed in some countries, adopted by international agencies and used as a general rule in other entirely different contexts without considering the local situations and dynamics, sometimes reducing the frameworks to a bureaucratic tick mark without bringing in any intended change; for example, Cartagena Protocol, on public participation.[5]

Figure 1: The 'Beam-Balance' Metaphor to Examine Power Dynamics of Responsible Innovation



Source: Author's framework.

Conclusion

Nanotechnology R&D is already moving with a fast pace in the field of health and communication technologies. The promises for the betterment of agri-food system appear appealing and repelling at the same time. This could be attributed to the environment of distrust which prevailed during the agribiotechnology controversies in the last decade. As the advancements in the field of agri-nanotechnology are at the initial phase and the search for an efficient governance system still continues, learning lessons from agribiotechnology situation might be useful. The agribiotechnology scene in India, characterised by Bt cotton debate, Bt brinjal consultations and BRAI bill, suggests a rethinking of the science-society relationship. First, the visions and imaginaries of the 'future', which different actors employ to promote technology, need to be situated in the changing socio-cultural context and should take into account the alternatives and asymmetries which exist in society. Second, a broadening of the meaning and process of risk assessment is required in the face of uncertainties associated to emerging technologies. This calls for a move forward from a fact-based system of innovation governance to a value-based system. Third, a deeper understanding of the 'public' and 'protest' beyond the 'deficit' model is required, in order to device mechanisms and institutions for science-society engagement.

The messages from the agribiotechnology scene in India echo with the emerging international discourses on RI. The critical debates on RI worldwide implicate about its potential to develop as an international governance paradigm in the context of emerging technologies. This article suggests that the time may be ripe for Indian nanotechnology discourse to engage with the debate on RI in order to 'move forward responsibly'. The article through the metaphor of 'beam-balance', tries to highlight the need to engage critically with the power dynamics imbibed in RI while using it as framework for finding a balance between harnessing the positive aspects of emerging technologies and minimising the adverse effects.

Endnotes

1 The phrse 'moving forward responsibly' has been used by Prof. Jennifer Kuzma (2005) where she is discussing the need for an oversight of the bio-nano interface. This article along with arguing for the above, projects the need to look back at the agribiotechnology situation to gather reflexive insights in order to illuminate the transition from biotechnology to nanotechnology in agriculture.

2 'Risk' is conceptualised broadly, as "the potential for realisation of unwanted, negative consequences of an event" (Rowe 1977) and 'probability times the magnitude of the hazards' (Scoones 2006). Risk has many dimensions such as severity, immediacy, spatial and temporal distribution and reversibility.

3 Public Perceptions of Agricultural Biotechnology in Europe project (PABE, available at: http://www.lancs.ac.uk/depts/ieppp/pabe/), which looked at underlying public concerns in five countries: France, Germany, Italy, Spain and the UK, Prajateerpu in Andhra Pradesh (Pimert and Wakeford 2002).

4 Personal communication with Andrew Stirling, Professor of science and technology policy at Sussex University. SPRU, Sussex, UK.

5 For details see Pandey 2013.

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RIS
Research and Information System
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Asian Biotechnology and Development Review
Vol. 15 No.3, pp 103-110

Forum

Ten Lessons from Biotechnology Experiences in Crops, Livestock and Fish for Smallholders in Developing Countries

James D. Dargie*, John Ruane** and Andrea Sonnino**

Abstract: : FAO recently commissioned a unique series of 19 case studies where agricultural biotechnologies were used to serve the needs of smallholders in developing countries. Most involved a single crop, livestock or fish species and a single biotechnology. The biotechnologies covered include some that are considered quite traditional, such as artificial insemination and fermentation, as well as other more modern ones, such as the use of DNA-based approaches to detect pathogens, but not genetic modification. From the case studies, we have drawn ten general and interrelated lessons which can be used to inform and assist policy-makers when deciding on potential interventions involving biotechnologies for smallholders in developing countries. These include: the absolute necessity for government commitment and backing from donors and international agencies, and of partnerships, both nationally and internationally, and also with the farmers themselves in the planning and implementation of programmes while bearing in mind also the need to retain flexibility in order to respond appropriately to evolving circumstances; and the recognition that while long-term investments in science and technology are critical, the successful use of biotechnologies also requires their appropriate integration with other sources of science-based and traditional knowledge. For the 19 case studies, there were no indications that intellectual property issues, access to genetic resources or specific regulatory mechanisms constrained use of any of the biotechnologies or their products. It was also concluded that planning, monitoring and evaluation of biotechnology applications was weak and should be strengthened.

Key words: Biotechnology, crop, livestock, fish, smallholders, developing countries

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The views expressed in this article are those of the author(s) and do not necessarily reflect the views of FAO. The authors are grateful to the scientists worldwide who prepared the 19 case studies and to our FAO colleagues D.M. Bartley, P. Boettcher, H.P.S. Makkar and C. Mba who contributed to coordinating their preparation.

Introduction

The latest State of Food Insecurity in the World report (FAO, IFAD and WFP 2013) indicates that although further progress had been made in reducing hunger, over 840 million people still suffered from chronic hunger in 2011-2013 and did not have enough food for an active and healthy life. The vast majority of hungry people live in rural areas in developing countries. While the current global food security situation is, therefore, quite critical, the future also promises very serious challenges which can exacerbate it considerably. The demand for food is expected to increase while the agriculture sectors, including forestry and fisheries, are expected to produce more non-food products, especially for energy and feed. At the same time, the natural resources needed for agriculture, such as available land, water and fertile soil, are threatened by numerous factors, including environmental degradation, climate change, urbanisation and loss of biodiversity and ecosystem services (Place and Meybeck 2013).

Research systems have to try to provide solutions to these major complex long-term problems, including how best to achieve 'sustainable intensification', whereby food production is increased in an sustainable way from existing farmlands (Garnett *et al.* 2013). It is widely held that agricultural innovation, encompassing the use of new processes, products and technologies, can play a key role in helping developing countries to face these future challenges (World Bank 2011). Agricultural biotechnology offers a suite of innovations whose potential contribution in this context has often been highlighted - see FAO (2011) or Ruane and Sonnino (2011) for further details.

In order to provide useful information for future interventions involving agricultural biotechnologies, we present here a summary of lessons learned from a Food and Agriculture Organisation of the UN (FAO) study of 19 cases describing the practical realities and experiences of applying biotechnologies for smallholders in different parts of the developing world (Ruane *et al.* 2013). They were chosen after a widely disseminated open call for proposals of case studies in which biotechnologies were applied to serve the needs of smallholders in developing countries (i.e. where they had progressed past the research or laboratory stage and were actually used in the field). The case studies were prepared by scientists and researchers directly involved in the initiatives who were asked to describe the background, achievements, obstacles/challenges encountered, factors for success (or failure), impacts and lessons learned from their case study.

Case Studies

The cases covered different world regions, production systems, species and underlying socio-economic conditions in the crop (seven case studies), livestock (seven) and aquaculture/fisheries (five) sectors. Apart from one on West Africa, the studies focused on a specific initiative within a single country. Four were from India, two from China and one each from Argentina, Bangladesh, Brazil, Cameroon, Colombia, Cuba, Ghana, Nigeria, South Africa, Sri Lanka, Tanzania and Thailand. More details on the different case studies are provided in Ruane *et al.* (2013).

A wide range of biotechnologies was used in the case studies, including some of the oldest or "traditional" methods, such as fermentation and artificial insemination, as well as several now at the forefront of "modern" science involving sophisticated DNA and genetic analyses, although not including genetic modification. GMO applications were not included because of the highly polarised debate they normally engender in discussions regarding agricultural biotechnologies, even when the term is defined in a very broad sense as here. By dominating the debate, this has prevented serious consideration to be given to the potential contributions that the many non-GMO biotechnologies can make to sustainable development and food security (Ruane and Sonnino 2011). To avoid this problem, we chose not to include them here and to instead dedicate other work activities exclusively to GMOs (e.g. Ruane 2013).

Most of the case studies involved application of a single biotechnology in a single crop, livestock or fish species. They included applications of biotechnologies to overcome biological and technological constraints to increase productivity, improve people's livelihoods, tackle diseases and pests, expand market opportunities through diversification and value addition, and to conserve genetic resources.

The case studies yielded many varied and valuable outputs, in terms of the scientific and technical knowledge, capacities and products that were generated. Collectively, these outputs had great potential for improving on-farm productivity, market access and livelihoods. While evidence of significant outcomes (i.e. widespread adoption or use of the products by farmers and supporting partners) was not convincing in all cases, some biotechnologies, particularly in relation to seed crops and fish, were certainly adopted on a large scale.

For example, two case studies described the use of molecular markers to assist genetic selection (í.e. 'marker-assisted selection') in pearl millet and rice for smallholders in India. In pearl millet, a new hybrid called HHB 67 Improved, developed in partnership by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Indian agricultural universities and British research institutes, was released by the Indian government for cultivation in 2005. By 2011, cultivation of this high yielding and downy mildew resistant variety had spread to almost 900,000 ha of land in northern India and it was estimated to have brought greater food security to about two million people.

In rice, partnerships between the International Rice Research Institute (IRRI) and Indian research institutes led to the commercial release of the Swarna-Sub1 variety in 2009. It is highly tolerant to submergence and lodging and, in flood-affected areas, was able to produce 1-3 tonnes of more rice per hectare than other varieties previously grown in rainfed lowlands. Around 38,000 tonnes of Swarna-Sub1 seed were produced in 2011, reaching over three million farmers and covering over one million ha of land during the 2012 wet season.

In aquaculture, a case study from China was dedicated to the Jian carp, developed by within-family genetic selection and gynogenesis (a reproductive technology resulting in all-female carp offspring which have received genetic material only from their mothers). The high-yielding fish is now grown on about 160,000 farms and is responsible for over 50 per cent of the total common carp production in the country.

In other areas, such as livestock and vegetatively propagated crops, the rate of adoption indicated in the case studies was less spectacular but nonetheless meaningful to the farming communities concerned. For example, in Bangladesh, one case study described a community-based foundation that provides production-related veterinary services, including artificial insemination, to around 3,000 smallholder dairy cattle farmers.

The initiative increased milk production and farmers' income and generated employment in a country where rural unemployment is a major problem.

Lessons Learned

From all the case studies, we have drawn ten general and interrelated lessons which can be used to inform and assist policy-makers when deciding on potential interventions involving biotechnologies for smallholders in developing countries. These are:

1. Commitment by national and/or state governments was critical for improving the productivity of smallholder enterprises and the livelihoods of smallholder farmers.
2. Financial support from bilateral and multilateral donors and international agencies was indispensable for supplementing national efforts.
3. International and national partnerships were vital for achieving results, particularly for translating research outputs into field outcomes and impacts. The case studies provided numerous examples of successful partnerships both within the public sector and involving international and national collaboration; between public and private sector entities; and involving NGOs and community-based approaches.
4. Long-term national investments in both human capital and infrastructure for science and technology were critical components of the recipe. The case studies involved continuous agricultural research efforts that extended over 15 to 40 years.
5. Biotechnology approaches did not work in a vacuum, but instead were introduced into both the research mix and farmers' fields through appropriate integration with other sources of science-based and traditional knowledge. For example, in the case studies using molecular markers, sound knowledge was also required of how to select parents, make crosses and backcrosses. All the biotechnologies required a good understanding of traditional procedures for plant, livestock and fish selection and breeding. Also, the accomplishments described would not have been possible without the knowledge, skills and support of the smallholder farmers themselves.

6. The diffusion of genetic resources, techniques and know-how across national and continental boundaries was an essential ingredient of most case studies. The case studies described significant transfer of germplasm across continents and individual countries (e.g. of cassava plantlets from Colombia to Nigeria). There were, however, no indications of difficulties regarding access to, and the use of, genetic resources in the 19 case studies considered in the publication.
7. Intellectual property issues did not constrain research or the production or use of biotechnology innovations in the case studies examined here. The issue of intellectual property rights (IPRs) was rarely mentioned suggesting that it did not hinder use of the biotechnologies. Note, however, that by definition all of the case studies chosen involved actual application of the biotechnologies in the field, and so represented a positive statistical sample. We cannot, therefore, exclude that IPRs might represent a barrier in some other projects, either preventing their initiation or their arrival to the application phase.
8. Products generated through the biotechnologies described did not need to conform to new biosafety or food safety regulations or standards. None of the case studies indicated that the processes and products from the biotechnologies required new national laws and regulations covering R&D, human, animal or plant sanitary issues or labelling. Without entering into the merits of such regulatory issues, this clearly represents an advantage for the development and use of products from the biotechnologies described in these case studies over those developed using genetic modification.
9. Over time, the "goalposts" sometimes moved, requiring both foresight and flexibility. Some case studies demonstrated clearly that development projects involving smallholder farm production systems can be dynamic and risk-prone and that stakeholders need to be aware, and anticipate, that the system may evolve quickly because of issues like changes in plant or animal disease dynamics or changes in farmer and consumer preferences. For example, in one case study, the breeding programme to improve the reproductive performance of the Deccani sheep in Maharashtra state in India had to be modified underway as farmers developed a preference for larger sheep of another breed.

10. Planning, monitoring and evaluation of biotechnology applications were weak and should be strengthened. Most of the studies provided no information concerning the costs or benefits (in terms of production, productivity or financial returns) or changes in livelihoods. To improve both the planning and management of future projects, these aspects should be given much higher priority by countries and their institutions.

Conclusion

In 2010, FAO organised an international technical conference on agricultural biotechnologies in developing countries (FAO 2011; Ruane and Sonnino 2011). At the end of the conference, the Member Nations reached a number of key conclusions. Among these, they acknowledged that agricultural biotechnologies can help to alleviate hunger and poverty; assist in adaptation to climate change and in maintaining the natural resource base; that agricultural biotechnologies have not been widely used in many developing countries, and have not sufficiently benefited smallholder farmers and producers and consumers; and that more R&D of agricultural biotechnologies should be focused on the needs of smallholder farmers and producers. The case studies in Ruane *et al.* (2013) demonstrate that despite the complexities of small holder farmer production systems, agricultural biotechnologies can indeed represent powerful tools to benefit smallholder farmers given the appropriate conditions and enabling environment. We hope that the case studies and the lessons learned from these studies may provide guidance and inspiration for policy-makers in the future.

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Asian Biotechnology and Development Review
Vol. 15 No.3, pp 111-116

Report

Africa-India Cooperation for Science, Technology and Innovation

22 October 2013, New Delhi

The conference on Africa-India Cooperation for Science, Technology and Innovation held in New Delhi on 22 October 2013 was organised by Research and Information Systems for Developing Countries (RIS) in collaboration with The Energy and Resource Institute (TERI), The New Partnership for Africa's Development (NEPAD) and Michigan State University (MSU), which had participants from diversified fields including academia, business and industry circles and representatives from the Indian and African governments.

In his welcome remarks, Dr. Sachin Chaturvedi, Senior Fellow, RIS highlighted the importance of issues pertaining to India-Africa cooperation in agricultural biotechnology and coordination of policy programmes in Africa. He outlined the challenges and stressed on the need of addressing the impact of technology as there has been a huge debate on science and technology and the social role it plays. He underlined that technology assessment should be done in an appropriate manner and there should be a balanced perspective on technology. He further mentioned about the RIS programme on science, technology and development that has been launched with the objective of promoting South-South cooperation. Dr. Biswajit Dhar, Director-General, RIS commented on the Indian engagements abroad, illuminating the fact that the dimensions of South-South cooperation are not new; India has been involved in assisting partner countries since 1990s. He also mentioned that there is immense potential for cooperation in the area of science, technology and innovation. Hence, more attention should be paid to them with a focus on institution building in partner countries.

Mr. Ravi Bangar, Additional Secretary, Ministry of External Affairs, Government of India began his inaugural address by highlighting India-Africa relations which date back to the pre-independence era. He mentioned, since the end of Cold War, a new era of cooperation, consultations and experience sharing has begun. India has committed to share experiences in the field of science, technology and innovation with Africa in addition to the bilateral exchanges through the India-Africa forum summit, highlighting a few examples, he mentioned about the Science and Technology Ministerial Conference, that took place in March 2012 and had over 150 delegates from over 40 African countries including 30 African ministers. The C.V Raman fellowship is also a flagship programme under which African scientists/ researchers come to India. Several other such programmes are there which highlight the success of India-Africa cooperation in various dimensions. India is committed not only to share the experiences, but also the best practices with Africa.

Dr. S.R. Rao, Advisor, Department of Biotechnology (DBT), Government of India, New Delhi in his keynote address, provided a historical overview of the plethora of programmes already in existence between Indian Science and Technology Ministry and the African continent, ranging from capacity building, human resources, knowledge sharing, research and development to several other areas. He stressed on the importance of the event involving six African countries and representatives from industries, business and governments of both the countries; and also highlighted the future pathways which can enhance the relationship between India and Africa. Dr. Vibha Dhawan, Executive Director, The Energy and Resources Institute (TERI) and Deputy Director, Borlaug Institute for South Asia (BISA), New Delhi extended the vote of thanks which was followed by the first session.

Professor Karim Maredia, MSU, co-chaired the first session on Institutional Initiatives in Africa with Professor Diran Makinde, African Biosafety Network of Expertise (ABNE) who briefly spoke about the ABNE programme which is a joint partnership between NEPAD and MSU, funded by Bill and Melinda Gates Foundation. Professor Diran also shed light on the initiative taken by the African Union and NEPAD to make Science, Technology and Innovation the epicenter for Africa's development. They further mentioned that there is not much technology infrastructure in Africa and wanted India to cooperate more in the form of collaborative innovation. Professor Maredia also talked about the "Freedom to Innovate" document of NEPAD and argued that science and regulation must co-evolve.

Dr. K.K Sharma, Principal Scientist, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, the first speaker for this session, briefed about the ICRISAT's work on agricultural R&D in the semi-arid tropics of Asia and Africa which has been going on for over last 40 years since 1972. He explained about the public-private partnership model for entrepreneurship development which has been the focus of ICRISAT for the past 10 years. He also presented an overview of how ICRISAT is trying to set up an ecosystem which would create inclusive market oriented development. He concluded his presentation by emphasising that ICRISAT would like to augment these initiatives and would like to continue this dialogue between India and Africa in the future.

Dr. Purvi Mehta, Regional Representative (South Asia), International Livestock Research Institute (ILRI), New Delhi started her presentation by highlighting the commonalties between India and Africa in terms of agriculture, challenges that are being faced by both and various trajectories that are followed in agricultural development. She then listed out a few concrete examples of the ongoing collaborations between India and Africa through ILRI. The India Mozambique Goats programme aims at developing the small ruminant sector in Rajasthan and Jharkhand, India and in the Vilankulo area of Mozambique. This programme has been in existence for the past five years and concentrates on developing the goat sector in both these countries. The milk India-Tanzania programme, which works right from the feed issue, is a South-South dairy collaboration bringing together the experiences of setting up dairy cooperatives in India and tailoring them to the needs of Africa. She concluded by saying that collaborations are important and common goals are to be achieved using these collaborations.

Dr. Anandajit Goswami, Coordinator, TERI Africa Centre for Global Agreements, TERI in his presentation underlined some of the initiatives that TERI has taken as part of its larger South-South cooperation programme which began in 1984, when TERI had partnered with an institution in Bangladesh and Shinhwa University. He talked of several other initiatives taken by TERI, where knowledge and partnerships were extended to partner institutions in Africa. The organisation has set up solar charging stations in Kenya and Mozambique which cater to more than 50 households and children are able to learn better through provision of light. Dr. Goswami also talked about "The South-South Knowledge Exchange", which aims to integrate diverse regions and its people through this forum. The platform offers a unique opportunity to people from developing, least developed and emerging nations or those associated with these activities in these nations to voice their opinions and diverse perspectives on sustainable development, energy, resources, climate change, trade and sustainable development

Professor Jenesio Ikindu Kinyamario, Board Chairman, National Biosafety Authority, Kenya was the chair for the second session on Cooperation in Agricultural Biosafety. The first presentation was made by Dr. N.K. Dadlani, Director, National Seed Association of India, New Delhi, who began his presentation by mentioning about the newest partnership they have had with Africa which is aimed to put a robust seed system in place. He briefly illustrated the state of Indian seed industry which was virtually nonexistent half a century ago, but over the years, it has evolved as an industry which now involves thousands of farmers. This had started with the initiatives of Rockfeller and Ford Foundation beginning in 1950s-60s when they brought maize hybrids and other material which were tried in the Indian climate and were successful. He mentioned that the National Seeds Corporation was the first institutional mechanism for seed industry set up in the country in 1963 to handle all the material which was coming in for green revolution programmes. He laid emphasis on discussing a few key milestones in the evolution of the Indian seed industry. In his views, India has progressed substantially since 2000 in terms of the seed industry; the growth rate of the seed industry globally is around 7-8 per cent but India's growth rate is 14 per cent, and has invested significantly into R&D.

On the contrary, in Africa most of the seed systems are informal, farmer based and low yielding except for maize. In most of the crops farmer-saved seeds are used to a large extent which is one of the reasons for stagnant growth in improved technologies. But he also emphasised upon the fact that there is significant market potential in Africa, with current demand not being met by the local varieties. He also talked about Syngenta Foundation for Sustainable Agriculture (SFSA) Seeds2B Project which consists of a strong public sector research programme, linking farmer technology, which is sourced from other countries and gives access to distributors, seed multipliers, output markets and insurance. SFSA's current trials in West Africa were in three locations in Senegal where varieties from Ankur Seeds, Nirmal Seeds, Indo-American, Ganga Kaveri Seeds, SeedsCo, and East West Seeds, were taken and crops like sorghum, millet, sesame, sunflower, tomato, onion, carrot, cabbage and okra were tested. He ended his remarks by depicting a win-win proposition for both the countries as international seed companies gain new market: African farmers gain new varieties and African distributors gain new business.

Dr. Willy K. Tonui, Chief Executive Officer, National Biosafety Authority, Kenya began his remarks by highlighting Kenya's biotechnology programme which started in the year 2006. Kenya signed the Cartagena protocol in the year 2000 and ratified the protocol in 2003, and in the year 2009 Kenya adopted the bio safety law, the Bio safety act of 2009. He emphasised that enterprise development in Kenya cuts across all disciplines except the pharmaceutical industry. He also mentioned that so far no biotech crop has been commercialised but Kenya would welcome collaborations in this area. Mr. Fikre Markos, Deputy Director, Animal and Plant Health Regulatory Directorate, Ethiopia raised issues related to seed systems in Ethiopia. He admitted that the legislative framework is in place but it has not been able to take the country where it wanted to be. Government is ready to invest as the economy is largely dependent on agriculture and small farmers are the key players. In his views, quality seeds have the potential to transform the agriculture but for this collaborations are needed.

Professor Bamidele O. Solomon, Director, National Biotechnology Development Agency (NABDA), Nigeria, who was the last speaker of this session, briefly touched on the Science, Technology and Innovation policy in Nigeria and how it relates to biotechnology. The policy in Nigeria basically promotes the understanding of biotechnology and its applications for national development and to build capacity and capabilities, harness indigenous knowledge and natural products and commercial discoveries as well as to position Nigeria in the bio-genetic market all the way to ensure compliance with biosafety and bioethics guidelines in biotechnology R&D. He ended his remarks by mentioning that Nigeria is a country of 170 million people. The country would like to support such activities which would alleviate challenges faced by the commercial biotech products and to minimise the cost of production.

The last session on STI Framework: Opportunities and Challenges was chaired by Dr. Sachin Chaturvedi, Senior Fellow, RIS. The session broadly looked into the STI framework in addition to the agricultural biotechnology to develop S&T indicators. Among the speakers, Dr. Sulakshana Jain, Scientist, Department of Science and Technology (DST), Government of India explained the science structure in India along with the objectives and functions of DST. She briefly highlighted the achievements of Indian science by showcasing the improvements in paper publications and patents data. She mentioned about the policy goal of ensuring faster, sustainable and inclusive growth (SHRISTI). She also pointed out the key elements of STI policy 2013 which talks about the scientific temperament, private sector participation in R&D, etc. On the issue of challenges, she mentioned about impact output assessment, integration of stakeholders, balancing innovation between global competition, inclusion and capacity building. On similar grounds, Professor Gnissa Isa Konate, Minister of Scientific Research and Innovation, Burkina Faso talked about the capacity building in human resource and research facility and gave insights on the STI structure in Burkina Faso. The final speaker of the session, Mr. George Tonderai Marechera, Africa Agricultural Technology Foundation (AATF), Kenya presented the mechanism for facilitating access and delivery of appropriate agricultural technologies for small holder farmers in Africa. AATF generally identifies the areas where the institutional mechanisms are in place; their investors include Rockfeller Foundation, US Agency for International Development (USAID), DFID, Bill and Melinda Gates Foundation, Partners for Innovation and Syngenta Foundation. He emphasised that India-Africa cooperation can be extended in priority areas like climate change, pest management, soil management and improvement in food quality.

The concluding session was an interactive session with Dr. C.D. Mayee, Ex-Chairman, Agricultural Scientists Recruitment Board. He presented a case study on “A Direct Farmers’ Perception of Bt Cotton” where he highlighted issues related to technology change in cotton growth and a parallel change in the production. According to Dr. Mayee, with the advent of new technologies, production has increased with time. He argued that the decade of the Bt adoption in India was a decade of success with cotton yields reaching the peak. He discussed several factors and pointed out the benefits of Bt cotton farming, constraints encountered by Bt cotton, economics of Bt cotton cultivation, attitude of farmers towards cultivation of Bt cotton, awareness about other biotech crops, etc. He concluded his presentation by giving recommendations that should support the public private partnerships (PPP) model of biotech/GM crops development, approval and commercialisation in the current scenario.

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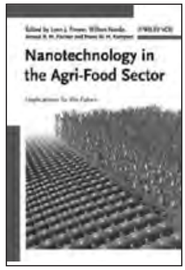
RIS
Research and Information System
for Developing Countries

Asian Biotechnology and Development Review
Vol. 15 No.3, pp 117-119

Book Review

Nanotechnology in the Agri-Food Sector: Implications for the Future



Editors: Lynn J. Frewer, Willem Norde, Arnout Fischer, and Frans Kampers
Publisher: Wiley-VCH
Year: 2011
No. of Pages: 328
ISBN No.: 978-3-527-33060-7
Price: $ 135.00 (Hardcover), $ 109.99 (E-book).

This edited book offers an introduction to the integration of nanotechnology into the agri-food sector along with the analysis of associated risk, public engagement and ethical considerations involved. Though there are other books also on the related topic such as Chaudhry's *Nanotechnologies in Food* (2010) and Huang's *Nanotechnology in the Food, Beverage and Nutraceutical Industries* (2012), this book has succeeded in dealing with the application of nanotechnology in both, agriculture and food sectors by covering all aspects of nanotechnology applications in food and agriculture. This book has four parts with seventeen chapters in total. The parts have been structured in a way to first provide the readers with the fundamentals of the nanotechnology before dwelling into its application in agri-food sector. The book opens with an introduction by the editors where they brief the readers about the advancement of nanotechnology, both as basic and applied science, and the concerns that are being raised about the safety of human health and environment.

Part One introduces the fundamentals of nanotechnology, where it talks about intermolecular interactions and supramolecular structures. This part provides an elementary understanding about the functioning of nanotechnology.

Part Two deals with the basic applications of nanotechnology, particularly in food production, packaging and agriculture and food diagnostics. In the Chapter on Nanotechnology in Food Production, Boom mentions the various potential ways in which the nanotechnology can be applied for food processing, packaging, nutritional enhancement and waste management. He briefly mentions about the risks, but says that owing to no conclusive evidence "the emergence of nanostructured food components shows no reason for caution any more than the development of any new component would merit" (p. 55). In the Chapter on Packaging, Kampers specifically talked about application of nanotechnology in food packaging highlighting its role in ensuring quality and preventing spoilage and contamination. He compared nanotechnology with other existing technologies for food packaging and concluded that nanotechnology is a better option. However, in the case of environmental risk that it can pose, the author argues that "before large-scale application of persistent nanoparticles in food packaging applications, more research is necessary to characterise these effects" (p.72). On ensuring consumer and societal acceptance of this application, he advocates for research on possible negative effects on human health, environment and socio-economic issues. In the subsequent Chapter on Using Nanoparticles in Agricultural and Food Diagnostics, Posthuma-Trumpie *et al.* gave the technical aspects of how this application can be made possible.

Part Three specifically deals with the Food Applications of nanotechnology. This part has four chapters (Chapters 6-9) which broadly covers the nanotechnology applications in agriculture, food improvement and nano-food product commercialisation. In Chapter 6, authors O'Brien and Cummins explore nano-based techniques which can be employed in crop and livestock production for improving food productivity, traceability and safety. In Chapter 7, authors Robinson and Morrison talk about the potential application of nanotechnology for improving food quality, safety and security in the domains of agricultural production, food processing, and packaging and distribution. Chapter 8 deals with the technical details relating to food functionality and the physics of bionanotechnology. The last chapter in this Part covers the commercialisation aspects of nano-food products, where Bugusu *et al.* discuss the path to commercialisation and the challenges therein.

Finally, Part Four (Chapters 10-17) discusses the broader issues concerning societal engagement with nanotechnology. Along with discussing the potential benefits of nanotechnology, this part deals with the emerging risks and the mechanisms to ensure safety. Chapter 10 specifically covers the toxicological concerns of nanomaterials in food. It comes up with certain validation parameters to toxicological implications of the nanomaterials. Authors argue for global collaborations: “Globally, the scientific and industrial communities need to come together to resolve the issues of safety of nanomaterials in food” (p. 185). Chapter 11 deals with the potential implications of nanomaterials in food and food contact materials for consumer safety and regulatory controls. Chapter 12 is based on the issues related to environment and the societal reactions to the nanotechnology applications in the food sector. In Chapter 13, Mills *et al.* point out the need for nanoparticles in food to undergo an allergenicity risk assessment to minimise any allergic reactions on its consumption. Chapters 14 and 15 broadly highlight various aspects of the communication, public perception and public engagement in the sphere of emerging technologies such as nanotechnology and its applications particularly related to agri-food sector. Chapter 16 deals with nano-ethics. Here the author describes the ethical challenges that are there for the nano-agri-food sector which includes ethical issues such as injustice, inequity, etc. that can arise from the nanotechnological products or processes. Finally, the Chapter 17 attempts to evolve a risk governance framework by bringing together the three activities of risk analysis, i.e. risk assessment, risk management and risk communication.

Overall, this edited volume integrates the technical aspects with the potential applications and policy challenges that nanotechnological applications can pose. To sum up, it can be said that from the public policy point of view, this book had captured various regulatory issues and underlines the importance of timely and extensive risk-safety research, wider consultation and public engagement. However, in terms of the structure, the book seems to be slightly unorganized, in a sense that in almost all the chapters the running theme is about the potential benefits and risks relating to nanotechnology application in agri-food sector. This results in overlapping of the similar arguments which could have been avoided. Still the book is an interesting, and informative volume and is recommend to researchers, students, academics, entrepreneurs, industries and policy makers interested in the issues related to the application of nanotechnology in agri-food sectors.

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Guidelines for Contributors

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3. Use 's' in '-ise' '-isation' words; e.g., 'civilise', 'organisation'. Use British spellings rather than American spellings. Thus, 'labour' not 'labor'.
4. Use figures (rather than word) for quantities and exact measurements including percentages (2 per cent, 3 km, 36 years old, etc.). In general descriptions, numbers below 10 should be spelt out in words. Use thousands, millions, billions, not lakhs and crores. Use fuller forms for numbers and dates— for example 1980-88, pp. 200-202 and pp. 178-84.
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All references should be embedded in the text in the anthropological style–for example '(Hirschman 1961)' or '(Lakshman 1989:125)' (Note: Page numbers in the text are necessary only if the cited portion is a direct quote).

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Hirschman, A. O. 1961. *Strategy of Economic Development*. New Haven: Yale University Press.

(b) Edited volumes:

Shand, Ric (ed.). 1999. *Economic Liberalisation in South Asia.* Delhi: Macmillan.

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(d) Articles from Journals:

Rao, M.G., K. P. Kalirajan and R. T. Shand. 1999. "Convergence of Income across Indian States: A Divergent View". *Economic and Political Weekly,* 34(13): pp. 769-78.

(e) Unpublished Work:

Sandee, H. 1995. "Innovations in Production". Unpublished Ph.D thesis. Amsterdam: Free University.

(f) Online Reference:

World Health Organisation. 2000. "Development of National Policy on Traditional Medicine". Retrieved on March 31, 2011 from http://www.wpro.who.int/sites/trm/documents/Development+of+National+Policy+on+Traditional+Medicine.htm

Asian Biotechnology and Development Review (ABDR) is a peer reviewed, international journal on socio-economic development, public policy, ethical and regulatory aspects of biotechnology, with a focus on developing countries. *ABDR* is a forum for informed contributions and discussions and is an academic journal with a public policy orientation. Published three times a year, *ABDR* is supported by UNESCO. It is published by Research and Information System for Developing Countries (RIS), a New Delhi based autonomous think-tank, envisioned as a forum for fostering effective policy dialogue among developing countries on international economic issues.

This special issue of the *ABDR* has the guest editorial and five articles that discuss about nanotechnology and nanobiotechnology in agriculture and food. The issues discussed herein include prospects of nanotechnology for enhancing water and nutrition security; health hazards associated with engineered nanomaterials; developments in bionanocomposite films and prospects for eco-friendly and smart packaging; public R&D system in India; and responsible innovation in agribiotechnology and agrinanotechnology in India. Besides, the article by James D. Dargie, John Ruane and Andrea Sonnino in the Forum Column discusses the lessons from biotechnology experiences in crops, livestock and fish for smallholders in developing countries. The issue also has a report on the conference on Africa-India Cooperation for Science, Technology and Innovation and a book review.

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