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Nanotechnology for enhancing food security in India

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ABSTRACT

A framework for assessment of the potential of nanotechnology for enhancing food security in India is developed. Agricultural productivity, soil health, water security, and food quality in storage and distribution are identified as the primary determinants of food security that can be impacted by developments in nanotechnology. The framework is developed in two stages: (i) mapping nanotechnology to agri-food thematic areas across the agricultural value chain and (ii) from the thematic areas to the food security determinants. Using published literature and patents data, a model to organize and map nanotechnology research to the agri-food thematic areas and food security determinants is developed through a specially designed database. The model allows identification and prioritization of potential areas for nanotechnology applications to enhance food security. Comparisons of this technology with green revolution technologies and agricultural biotechnology indicate a possibility of greater and faster impact on all components of the agri-value chain with concurrent social, ethical, legal and environmental implications. There is a need for investments in capacity building and development of an agri-nanotechnology infrastructure in India, and for ex ante assessment of its implications for society.

Introduction

Food security is the state achieved when food systems operate such that 'all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life' (FAO, 1996). Food systems encompass three components: (i) food availability (production, distribution and exchange) (ii) food access (affordability, allocation and preference) and (iii) food utilization (nutritional value, social value and food safety) (Gregory et al., 2005). Food security is diminished or a state of food insecurity occurs when any one of the three components of the food systems are diminished.

Cycles of food insecurity were common in India prior to the green revolution era in the 1970s. The revolution laid the foundation for food security in India through dramatic increases in food production. The success of the green revolution technologies during the 1970s and 1980s is attributed to a technology model together with adoption of concurrent micro and macro-economics models. The micro or farm economics governed the use of inputs such as land, cultivars, labor, machinery, and chemicals, balanced against profits from crop yields. The macro-economics ensured better prices to farmers and access to inputs and markets (Mehta, 1997). While the green revolution technologies model addressed the first component of food security, the second component was addressed through policy interventions in the form of foodgrain subsidies that ensured large buffer stocks, and access to low priced food through an effective Public Distribution System (PDS). During the late eighties, rising incomes in certain sectors of population also gave scope for a diversified food basket leading to a sharper increase in the production of meat, milk and eggs. These early increases in per capita food availability have led to a positive feeling that food security concerns of the increasing populations in India could be addressed successfully. In case of the third component of food security–food utilization, which is essentially a household level concern, there has been relatively less emphasis and nearly one fifth of the population are stated to be undernourished.

Concurrently, the recent declines in agricultural growth from about 3.6% during 1985–1995 to less than 2% in the decade 1995–2005 (Planning Commission, 2007a) have given rise to renewed concerns about future food security. Major areas of concern are production and availability of food grains. The per capita annual production of cereals has declined from 207 kg in 1991/1995 to 186 kg in 2004/2007, and continues to show decreasing trends. The globalization of agricultural trade in the 1990s led to changes in some of the macro policies that supported agriculture and also subjected the Indian farmer to significant market risks. All of these have led to a steady decline in farm incomes and rural distress in recent years, affecting both access to food and its utilization. It is vital to increase and stabilize agricultural incomes for

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overall national growth, as this sector still employs over 50% of the Indian work force. The problems are being compounded by degradation of the natural resource base (soil, water and climate) of agriculture. The difficult situation in Indian agriculture has been described by the Planning Commission of Government of India in its XI Plan strategy paper as an 'agricultural crisis' resulting from a 'technology fatigue' (Planning Commission, 2007b). With the limited availability of land and water resources emerging at this time, the national policy goal of 4% growth in agriculture to ensure food security can be achieved only by increasing productivity and incomes per unit of the scarce natural resources through effective use of improved technology in the rural sector. This requires ensuring the continuous flow of new technologies into this sector (Mitchell, 2001).

Among the many advancements in science, nanotechnology (NT) is being visualized as a rapidly evolving field that has potential to revolutionize food systems (Roco, 2003; Opara, 2004; Ward and Datta, 2005; Kuzma and Verhage, 2006; Scrinis and Lyons, 2007), and improve the conditions of the poor (UN Millennium Project, 2005). Nanotechnology is defined as the "understanding and control of matter at dimensions of roughly 1–100 nm, where unique phenomena enable novel applications" (Roco, 2003). 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, electronic, photonic and magnetic properties of nanoscale materials. The ability to manipulate matter at the nanoscale can lead to improved understanding of biological, physical and chemical processes at this scale and to the creation of improved materials, structures, devices and systems that exploit these new properties. A UN Survey on potential applications of nanotechnology in developing countries identified agricultural productivity enhancement as the second most critical area of application for attaining the Millennium Development Goals of eradicating hunger and malnutrition (Salamanca-Buentello et al., 2005). For India, it is also important that investments in nanotechnology are made to ensure that the National Agricultural Research System stays globally competitive. The objective of this paper is to assess the scope for enhancing food security in India through the application of nanotechnology.

Food security in India: concerns and determinants

There are 854 million food-insecure people globally, of which a third live in India (Cakmak, 2002; Borlaug, 2007). In addition to rising demand for food resulting from increasing population and economic growth, increased risks of food insecurity are foreseen from: an estimated rising global energy demand of 50% to 2030 (Hightower and Pierce, 2008), a decline in per capita availability of arable land from 0.40 ha in 1961 to 0.25 ha in 1999 (Horrigan et al., 2002), a decreasing renewable fresh water supply (Barnett et al., 2005), and projected climate change impacts (Parry et al., 2004; Rosenwzeig and Parry, 1994). The MSSRF and the UN World Food Programme (WFP) have developed three Atlases (MSSRF, 2004) using chosen indicators to map the relative standing of food insecurity in the 23 states of India. The atlases indicate alarming overexploitation of water and other natural resources, declines in sown areas, degradation of lands, and low livelihood access with increasing poverty levels. India's National Hunger Index, which is based on the Global Hunger Index developed by IFPRI (Wiesmann et al., 2006) was 23.7 in 2008 (66th out of 88 countries). The Hunger Index for India (Menon et al., 2009) also highlights a continued severity of hunger across the country. Though variations in hunger index level are present across states, what is significant is that not even a single state showed low or even moderate level of hunger. This is of serious concern for a country with relatively high economic growth even in the days of global recession.

Determinants of food security in India

The three components of food security, namely availability, access and utilization are governed by the vulnerability of the production base of agriculture, the scope for increasing rural incomes and the nutritional quality of food respectively. The primary determinants of agricultural production are the genetic productivity of the crops, and the quality of the natural resource base determined by the soil health and vulnerability of water resources. Together these determine the total quantity of food available for consumption, storage and distribution. If any of these are vulnerable, the food availability is affected. Value addition is the main means for ensuring consistent rise in rural incomes, which controls the access to food. Access and utilization of food are determined by the ability to store and maintain the quality of produce over long periods of time. The extent to which the quality of the food is retained in storage and distribution therefore controls the third component of food security, namely, utilization. Thus, productivity, soil health, water security, and food quality in storage and distribution can be viewed as key determinants of food security. Nanotechnology can potentially impact all the four key determinants of food security.

Nanotechnology and food systems

Since food systems encompass food availability, access and utilization, the scope of applications of nanotechnology for enhancing food security must encompass entire agricultural production–consumption systems. Further, in a rapidly globalizing economy, increasing access to food and its utilization in rural areas will be determined primarily by increase in rural incomes. The primary source of increasing rural incomes has been recognized as value addition across the different links in the agricultural production–consumption chain (Planning Commission, 2007a,b). These links include farm inputs, farm production systems, post harvest management and processing and finally markets and consumers. From the food security perspective, it is therefore necessary that application of nanotechnology be *not limited to the farm production level, but be extended across all the links of the agricultural value chain to increase agricultural productivities, product quality, consumer acceptance and resource use efficiencies*. This will help to reduce farm costs, raise the value of production, increase rural incomes and enhance the quality of the natural resource base of agricultural production systems (Kalpana Sastry et al., 2007). In doing so, it is important to view nanotechnology as an enabling technology that can complement conventional technologies and biotechnology (Salerno et al., 2008). Considering the concerns on biosafety and consumer acceptance emerging after agribiotechnology based-products have entered the market place during last two decades, it is also essential that integrating and deploying new technologies like nanotechnology in agricultural and food systems be made after understanding the various societal and environmental implications (Kalpana Sastry et al., 2009, 2010a).

Green revolution technologies, biotechnologies and nanotechnology in food systems – a comparison

A comparison between green revolution technologies, biotechnologies and nanotechnology, based on key word searches of literature, is presented in Table 1 to illustrate the wider canvas over which nanotechnology can affect food systems. It may be pointed that in case of nanotechnology, results are from early researches and reflect expected potential assessed from the literature.

Table 1
Comparisons among green revolution technologies, biotechnology and nanotechnology with respect to their impacts and implications for food systems.

Characteristics	Green revolution technologies	Biotechnology	Nanotechnology[a]
Primary area of focus	Productivity of mainly cereal crops viz. wheat, rice, maize, sorghum	Productivity of all crops, including cereals, fibers, vegetables, fruits, export commodities, and specialty crops	Productivity and management of crops and livestock – crop and livestock improvement, precision agriculture, soil and water management, pest diagnosis/surveillance, food processing, food safety and packaging
Secondary area of focus	None	Animal and fish products, processed food products	Vaccines, pesticides, fertilizers, water, gene, drug, inputs for remediation of natural resources and other input delivery formulations in plants and animals; nanoarray based gene-technologies for gene expressions in plants and animals under stress conditions; utilization of agricultural waste
Applications	Crop input packages; improvement of plant architecture; genetic enhancement through conservative breeding	Tissue culture, micro propagation; transgenic crops/animals; MAS; biotechnology, proteomics	Areas of gene/DNA delivery, expressions, sequencing, therapy, regulation: DNA targeting, extraction, hybridization, fingerprints for DNA; RNA detection, cell probes, cell sorting and bioimaging, single-cell-based assay, tissue engineering, proteomics and nanobiogenomics
Parties in technology development and dissemination	Largely public or quasi-public sector	Substantial private sector involvement – industry concentration	Large public investments, relatively small scale private sector, venture, capital funds
Proprietary considerations	Patents and plant variety protection not important; free flow of germplasm	Many processes and products patentable and protectable, issues related FTO	High patent activity, increased controls
Capital costs of research	Relatively low	Relatively high	Extremely high; but partnerships can lower costs
Research skills required	Conventional plant breeding and other agricultural sciences	Molecular and cell biology expertise plus conventional plant breeding skills and expertise in other agricultural sciences	New knowledge and skill set in addition to conventional; new workforce to be created
Crops displaced	Traditional varieties and land races replaced by high-yielding varieties/hybrids	Traditional varieties and land races replaced by high-yielding varieties/transgenic/GM crops	Expected to enhance not displace crops
Access to information and resources	Relatively easy	Restricted due to IPR	Extremely restricted due to broad set of claims; several emerging grey areas in IP jurisprudence
Regulatory system	Not warranted	In place but through continuing opposition; still evolving	Evolving; not in place even at global level
Environment risks	Evidence for several negative effects on natural resources	Mixed conflicting reports	Clear data still not available
Ethical issues	Low to medium	Medium to high	Several suppositions; gray area needing attention
Socioeconomic risks	Gaps in reaching farmers with small holdings	Access to technology products; widening income disparity between small and large farmers; technology divide between developed and developing countries	Too early to derive conclusions; technology divide between developed and developing countries
Influence on society	Helped developing countries to be food – self-sufficient; prosperity in several strata of society	Aim poverty reduction through increased productivity; lower food prices and better nutrition	Expected to influence all levels and bring new paradigms in society
Public acceptance	All countries	Not acceptable in many countries of EU for food; mixed response in Asia	Initial protests by civil society started

[a] Based on indications in early research and projections forecasted.

The above comparison illustrates the enhanced pace and promise of more solutions being offered by the emerging technologies. The green revolution technologies were trendsetters over the traditional and conservative practices, but the focus was on cereals like wheat, rice, maize and sorghum. Biotechnologies provided an enhanced pace, and increased the scope of products /processes in other areas of agriculture including non-cereal crops and crops cultivated by the poor. The technologies expanded to several solutions in other sectors like veterinary, dairy, poultry and fishery sectors, which contribute to advancing nutritional security.

Nanotechnology points to an even wider canvas of agri-food systems. The nature of this technology indicates a likely greater impact on all levels of the agricultural value chain (SAiNSCE, 2009). The technologies also necessitate newer levels of knowledge and skills. Therefore, it warrants more investments on training of manpower, and on infrastructure. Further, with reduced access as a result of greater levels of proprietary rights, new models of governance would need to be evolved for effective delivery. Equally important are the gray areas of the risks to environment, vulnerability of users, and the society at large (NSF, 2001). The faster and increased pace of nanotechnology development brings new innovation cycles, which may threaten the existing socio-economic patterns and assume new dimensions at a higher magnitude than in the case of biotechnology (Linton and Walsh, 2008). The present regulatory system being followed in India for biotechnology is still evolving and continues to face challenges in its implementation and acceptance. In case of nanotechnology a more cohesive and proactive approach would need to be developed for its regulation.

Framework for assessing nanotechnology for enhanced food security in India

Assessment of emerging technologies like nanotechnology is difficult because historical data is not available for impact assessment and much of the work is at basic research stage with future promise of a range of applications. In such situations, bibliometrics and patent analysis can be used to both assess current status and trends in technology development, and classify and map them to relevant application areas for strategic planning (Kostoff et al., 2007; Daim et al., 2006; Hullmann and Meyer, 2003; Kalpana Sastry et al., 2010b). A general premise is that basic research is found largely in journals; where as potential commercial applications are found in patents. Patent documents are also well structured to provide standardized information about citation, issue date, inventors, institutions and their locations technology field classification, etc. Such structured documentation makes them suitable for assessing technology developments in various areas. Bibliometric data on the other hand is less precisely structured but amenable to formal key word searches and more intensive text mining approaches for technology assessment.

A holistic systems framework was developed for patent and bibliometric analysis for assessment of the potential of nanotechnology for enhancing food systems security in India. The framework was developed in two stages:

(i) Mapping nanotechnology to agri-food thematic areas across all the links of the agricultural value chain (that is, farm inputs, production systems, post harvest management including storing and processing, markets and consumption).
(ii) Mapping nanotechnology to the determinants of food security (productivity, soil health, water security and food quality).

Mapping nanotechnology to the agri-value chain

Based on technology roadmapping and database management concepts, a framework was developed earlier through an ongoing project on "Assessing Interrelationships between Developments in Nanotechnology and Agriculture" (NAARM, 2009) (Fig. 1). This was used to map nanoresearch areas to the agri-food thematic areas along the agricultural value chain (Fig. 1). A five-step approach was followed: (i) identification of nanoresearch based on a general survey of nanoresearch themes (Table 2) and agri-food thematic areas (Table 3); (ii) relating nanoresearch areas (Table 2) with the agri-food thematic areas (Table 3) through a filter of the links in the agri-value chain; (iii) design of database using MS access for R&D indicators like bibliographic sources and patents, to enable querying, analysis and mapping the technology trends based on both nanoresearch and agri-food themes; (iv) designing bibliographic search strategy to populate the bibliographic database; and (v) designing patent search strategy to build the patents database (Kalpana Sastry et al., 2010a). The framework and database allow for mining information in specific areas of application of nanotechnology in agriculture, and for assessing their environmental, ethical, legal and societal implications.

Mapping nanotechnology to the determinants of food security

In the present study, the framework developed above (Fig. 1) has been applied to map both patent and bibliographic information to the determinants of food security. For the two R&D indicators, bibliometrics and patents, independent databases were developed, which were

(i) bibliographic database of about 500 bibliographic sources and
(ii) patents database of about 1000 patents.

Then both these databases were sorted and organized to carry out the assessment. This was carried out with respect to the following factors viz, nanotechnology product (nanoparticles, nanotubes, quantum dots, etc.) and its characteristics; agricultural supply chain sector affected; possible social and environmental risks; time to commercialization; inventors, their institutes and location. A detailed analysis of the data in each of these areas can help to assess and identify relevant research tools, which can be integrated into the application. Based on this assessment, an

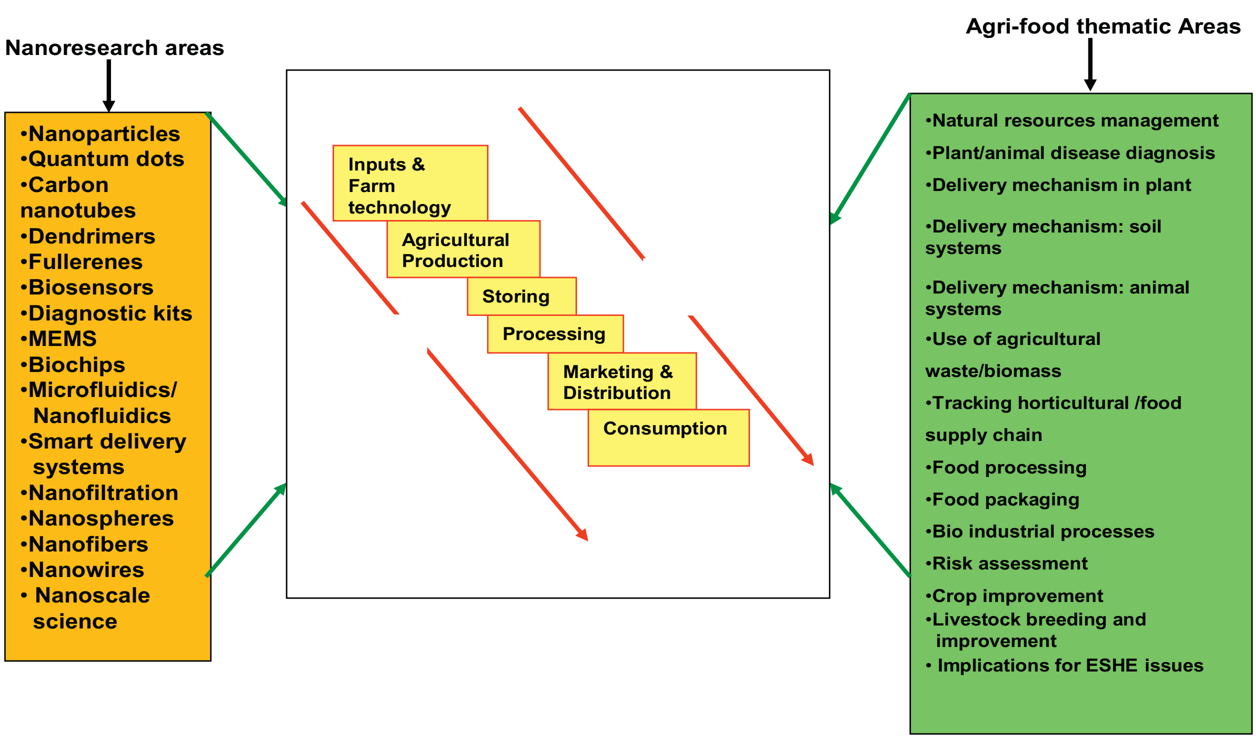

Fig. 1. Framework for integrating nanoresearch areas and agri-food thematic areas.

Table 2
Nanoresearch thematic areas of relevance to agri-food systems in India.

No.	Nanoresearch area
1	Nanoparticles
2	Quantum dots
3	Carbon nanotubes
4	Dendrimers
5	Fullerenes
6	Biosensors
7	Diagnostic kits
8	MEMS
9	Biochips
10	Microfluidics/nanofluidics
11	Smart delivery systems
12	Nanofiltration
13	Nanospheres
14	Nanofibers
15	Nanowires
16	Nanoscale phenomena and processes

Table 3
Key agri-food thematic areas with potential for nanotechnology applications.

No.	Agri-food thematic areas
1	Natural resource management- efficient use of soil, water, energy inputs
2	Plant/animal disease diagnostics
3	Delivery mechanisms in plant systems
4	Delivery mechanisms in soil systems
5	Delivery mechanisms in animal systems
6	Use of agricultural waste/biomass/byproducts
7	Tracking the horticultural/food value chain
8	Food processing
9	Food packaging
10	Bio-industrial processes
11	Risk assessment/safety
12	Developing new genetic types/breeds/cultivars
13	Livestock breeding and improvement
14	Ethical, social, legal, environmental implications

effort was made to identify and map areas of nanoresearch and agri-thematic areas to the determinants of food security identified earlier, namely, productivity, soil health, water security and retaining food quality in storage and distribution (Fig. 2).

Trends in nanotechnology development

The framework and databases were used to gauge the type of nanotechnology researches currently in progress and to assess them from the perspective of food security. More than 60% of records from both the databases were on R&D efforts to enhance plant/animal productivity followed by research in food processing and food packaging (Fig. 3) which address the other two components of food security systems, namely, food availability and food utilization.

The type of drivers of the technological changes in various sub fields of nanoresearch (like nanodevices or nanobiotechnology), which may form base for technological trajectories that can contribute to enhancing food security, was also investigated. It was found that nanoparticles was the most widely researched area followed by nanofiltration methods/devices and nanocapsules (Fig. 4). Formulations like capsules and particles are known to enhance target delivery, offer better control, and increase overall functional efficiency especially for inputs like fertilizers, pesticides including biopesticides, improving the management practices for enhancing productivity.

A more detailed analysis of the two R&D indicators, publications and patents, was carried out for possible applications in the agri-value chain. The analysis indicates a wide range of applications for harnessing the potential of nanotechnology for enhancing productivity, efficient use of water resources and for remediation processes of soils unfit for cultivation. In addition, there are early-stage researches being undertaken to enlarge the scope of value addition of processes in food industry and thereby increasing the nutritive and keeping quality of processed foods. A tabulated synopsis of potential applications using nanotechnology for enhancing the determinants of food security is presented in Table 4.

Based on these indications, some of the areas of nanotechnology with potential applications for enhancing food security in India are: nanofertilizers for slow release and efficient uptake of water and fertilizers by plants; nanocides–pesticides encapsulated in nanoparticles for controlled release, and nanoemulsions for greater efficiency; delivery of nutrients and drugs for livestock and fisheries; nanoparticles for soil conservation and remediation; nanobrushes and nanofilters for soil and water purification, cleaning of fishponds; and nanosensors for soil quality and for plant health monitoring, and nanodevices for precision agriculture. Application of nanotechnology is also possible in food processing as nanocomposites and nanobiocomposites for plastic film coatings used in food packaging, anti-microbial nanoemulsions for decontamination of food equipment, packaging and processing. All these technologies contribute to enhancing the four determinants of food security and in consequence catalyze the process for enhancing food security in India.

Technology transfer concerns

Patenting trends in nanotechnology

It is interesting to note that the trend in patenting in nanotechnology equals (or even exceeds) that for publishing, indicating that even early-stage research in this area is leading to technology protection before development and product commercialization. When compared to the era of green revolution technologies and later biotechnologies, nanotechnology research is leading to product development by the industries almost concurrently with basic research in this area. It is well recognized that patents are primary output of the R&D activities and patent analysis is now the most widely used methodology in formalized and systemic approaches to identifying and managing technological change (Choi and Park, 2009). Therefore, a more detailed assessment on the fields of technology was made by analyzing the distribution pattern of the patents in various subfields of categories under International Patent Classification (IPC, 2009). The patents were found in about 33 IPC classes (till subclass level or the third hierarchical level of classification) covering a large domain of sectors. The detailed analysis was restricted to those sections/classes with more than 20 records. It was found that highest percent (35) was in IPC class C12N which covers inventions based on microbes, and genetic material indicating increasing interest in researches in nanobiotechnologies (Table 5). This was followed by A61K (10%), which focuses on medicinal preparations. Indications of early developments in agriculture and food related areas, though at a lower intensity, were also found covered in A01H (New plants or processes for obtaining them; plant reproduction by tissue culture techniques); A01K (Animal husbandry; care of birds, fishes, insects; fishing; rearing or breeding animals and new breeds of animals); A01N (Preservation of bodies of humans or animals or plants or parts thereof; biocides, plant growth regulators); and A23 (Foods or foodstuffs and their treatment). This indicates that several patents are being filed for technologies, which have applications extendable to the

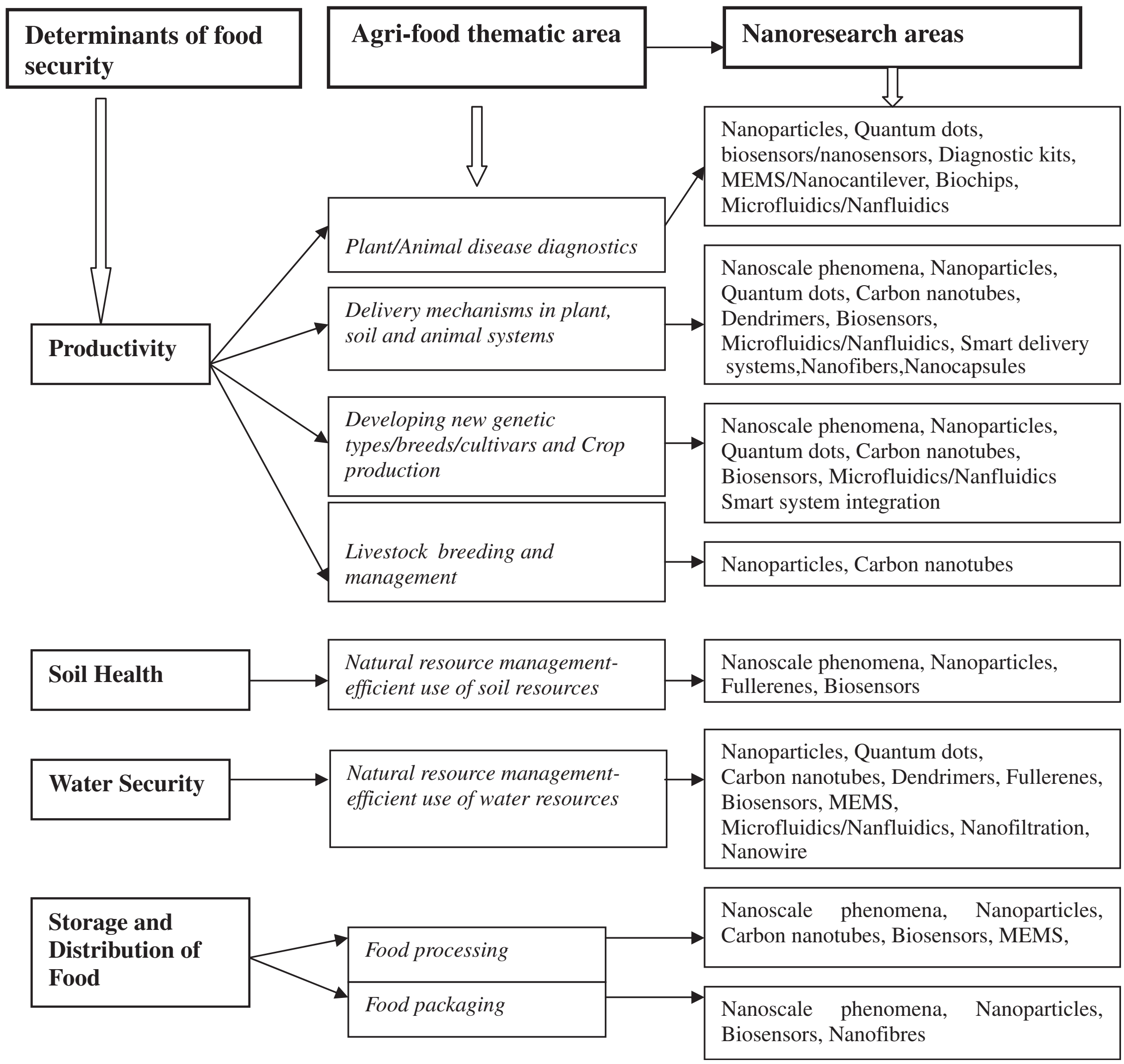

Fig. 2. Knowledge mapping framework for integration of food security determinants with nanoresearch areas across agri-food thematic areas.

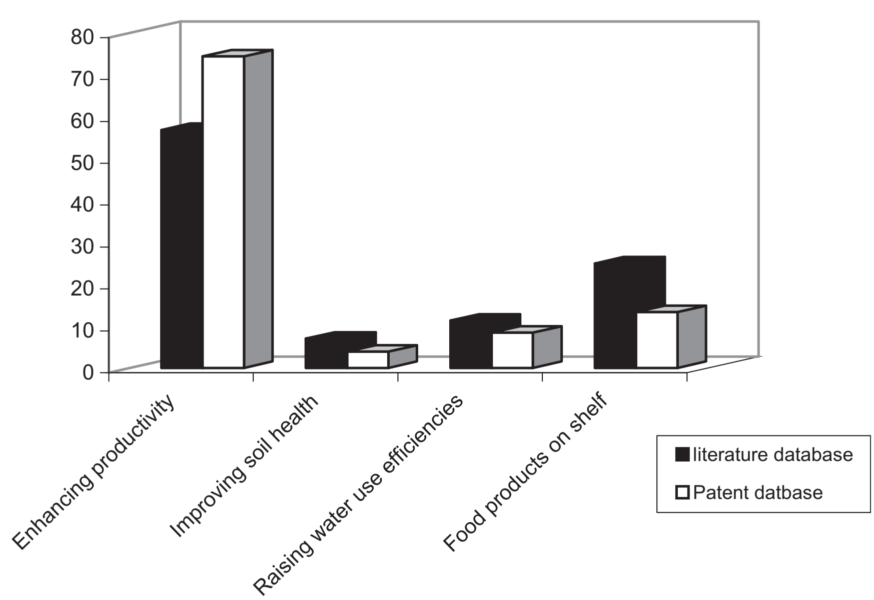

Fig. 3. R&D indicators of food security determinants.

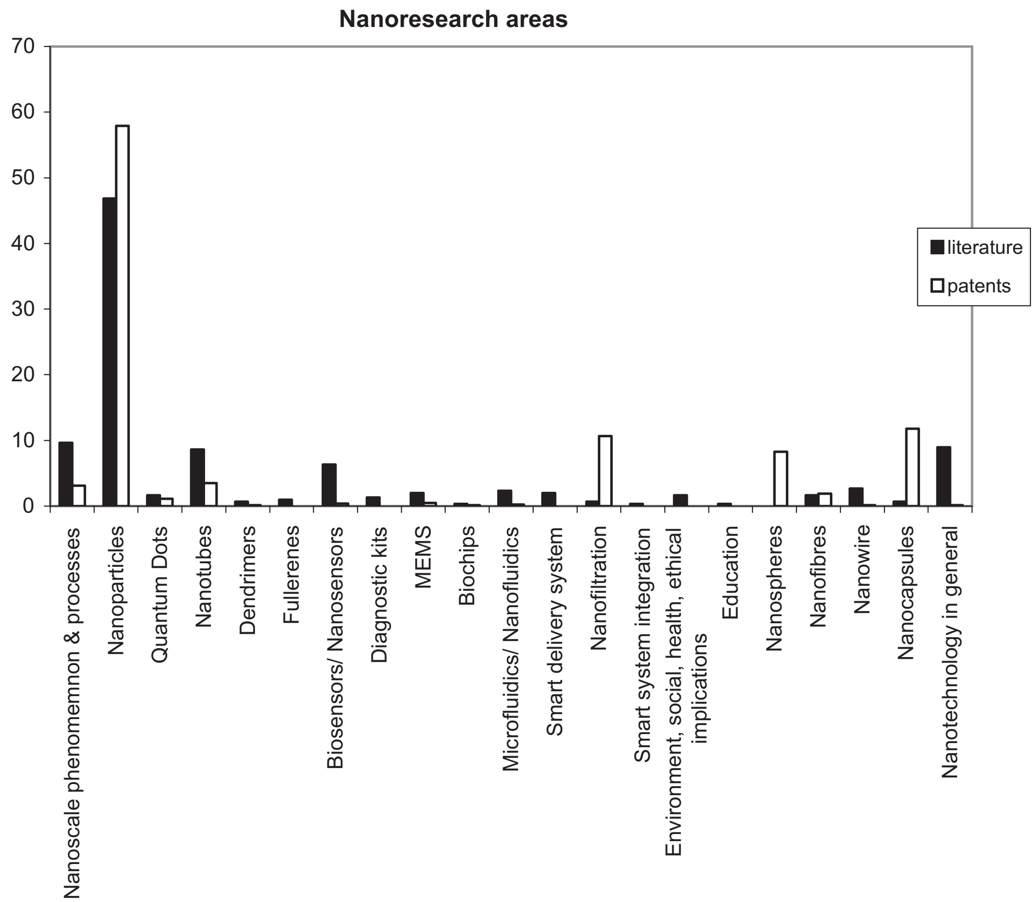

Fig. 4. Trends in R&D indicators of nanoresearch.

agriculture value chain. Given the breadth of the field and opportunity for broad patent coverage, intellectual property litigation over patents can be expected to emerge in the near future and the complexities seen earlier in agricultural biotechnologies may assume even a higher level in this field (Tullis, 2004).

Under these circumstances it can be a formidable challenge for the stakeholders including technology managers in the Indian agri-systems to harness the new technologies. Keeping in perspective, the emphasis on issues of IP and technology transfer in the Indian NARS (ICAR, 2006), the transfer processes of nanotechnologies in this sector against the patent portfolios may need to be well understood and policies developed before the commercialization cycles are put in place. These should be based on public involvement for interaction and discussions on the development and application of the regulatory governance structure rather than defensive reactions to criticisms in public or legal challenges as in the *Bt* technologies (Chowdhury, 2006). It is again emphasized that the use of this multi-faceted technology should be essentially focused to complement the current agri-production management. Thus, the complex technology transfer would also need sound research governance policies to address the expected and unexpected complications (Kalpana Sastry et al., 2010b). Developing open access models or encouraging use of proprietary ownerships on humanitarian licensing models can form part of technology transfer models (Brewster et al., 2007) to minimize the complications on technologies contributing for food security through stakeholder discussions from early-stage levels.

Environmental, social and health risks

New technologies and more so, high-end types like nanotechnology promise to offer significant benefits to humankind on one hand but can have possible risks of adverse and unintended consequences. The level of risk perceptions associated with nanotechnology was analyzed using the bibliographic database. The analysis indicated that the possible risks are of three types: environmental risks, social risks and health risks. These were indicated in almost a quarter of the publications (24%). Relative to the fast pace of nanotechnology development, evaluation of its possible risks has been slow. Since most of the nanotechnology applications in food security are expected to be based on its convergence with other technologies, the lack of science-based data on hazards and exposure pathways of nanobased technologies may be challenging to regulators in dealing with potential risks. Hence, it is essential that steps be taken to decrease scientific uncertainty of the potential risks through more investments in risk analysis. In addition, there is a need to involve the stakeholders in agri-value chain in the Indian context, from the early stages of technology development so that they are aware of the risks and uncertainties associated (Kalpana Sastry et al., 2010a). All these initiatives can lead to better understanding and acceptance of the products of research and catalyze the life cycle of technology development. As more technologies flow from this emerging sector, there would be more need for a coordinated risk management strategy.

Table 4
Nanoresearch areas and applications in agri-food sector which can contribute to enhanced food security.

Determinants of food security	Agri-food thematic areas	Nanoresearch area and indicative applications
Enhancing productivity	Plant/animal disease diagnostics	Nanobarcodes as ID tags for multiplexed analysis for gene expression and intracellular histopathology
		Quantum dots as fluorescence marker coupled with immunomagnetic separation for detection of *E. coli*
		Label-free sensor chip assembled from peptide nanotubes for electrical detection of low detection limit viruses
		Sensor array containing six non-covalent gold nanoparticles for detection and quantification of protein targets
	Delivery mechanisms in plant, soil and animal systems	Mesoporous silica nanoparticles for delivery of DNA and chemicals into plants
		Smart magnetic silica core for specific targeting, cell sorting and bioimaging
		Nanocontainers for delivery of drugs to organs or tissues
		Organically modified silica nanoparticles as DNA carriers, for gene delivery and promoters of transgene expression
		Carbon nanofibers for gene therapy of plants
		Oligonucleotide-loaded nanoparticles for enhancing the expression of rice α-galactosidase gene in yeast cells
		Micro/nanofluidic device-single-cell-based assay
		Carbon nanotubes as molecular transporters
		Tin oxide nanowires for water vapor detection
	Developing new genetic types/ breeds/cultivars and crop production	Atomically modified rice by drilling a nanosized hole through the wall and membrane of a rice cell for inserting a nitrogen atom
		Functionalized cow pea mosaic virus (CPMV) nanostructures for use in sensing applications
		Magnetic nanoparticles coated with tetramethylammonium hydroxide enhancing the growth of *Zea mays* plants in early ontogenetic stages
		Carbon nanotubes for experiments on artificial photosynthesis
		Blue shift of CdSe/ZnS nanocrystal-labels upon DNA-hybridization
	Livestock breeding and livestock management	Nanoparticles, nanocapsules and nanospheres in veterinary medicines
		Nanodevices implanted in an animal for detecting the presence of disease and notifying the farmer and veterinarian to activate a targeted treatment delivery system
Improving soil health	Natural resource management – efficient use of soil resources	Nanoparticles for soil in situ remediation
		Sorption and release of contaminants in the soil onto the surfaces of engineered nanoparticles
		Nanoscale iron particles for rapid destruction of chlorinated hydrocarbons in soil and groundwater
		Nanosensors for continuous monitoring of heavy metals
Determinants of food security	Agri-food thematic areas	Nanoresearch area and indicative applications
Raising water use efficiencies	Natural resource management – efficient use of water resources	Nanotechnology for desalination and water purification
		Nanoporous membranes for filtration of viruses
		Nanosponges to absorbs toxic metals
		Ozone nanobubbles to sterilize water
		Nanowire immunosensors array-for detection of microbial pathogens
		Ultra sensitive pathogen quantification in drinking water using high piezoelectric PMN-PT micro cantilevers
Food products on shelf	Food processing	Quick detection of food borne pathogens using bioconjugated nanomaterials, biosensor, nanocantilevers, carbon nanotubes, nanowires, BioMEMS
		Nanosensors for enhancing flavor and taste of the processed products
		Edible nanosensors for detection of bacterial contamination in the packaged foods
	Food packaging	Natural biopolymer-based nanocomposite films used for food packaging for safe storage
		Nanoscale titanium dioxide particles as blocking agent of UV light in plastic packaging

Conclusion

Food security is a primary policy concern for India and has engaged immediate attention of the national planners. Agricultural productivity, soil health, water resources and food packaging and storage would be four key determinants of future food security. Emerging technologies like nanotechnology can be focused on these four primary determinants to catalyze the research and develop a sustainable food security system.

The current trends in nanotechnology were assessed for their potential to enhance food security using R&D indicators like literature and patents mapped in a specially designed framework. The study indicates that nanotechnology has a larger canvas and greater potential to address food security as compared to green revolution technologies and biotechnologies. This is because of the enabling character of this technology that allows it to be extended across the agri-value chain (from farm to plate and vice versa). The study also indicated the need for more science-based

Table 5
Distribution of patents based on IPC classification.

IPC codes	Description	Percentage
A01H	New plants or processes for obtaining them; plant reproduction by tissue culture techniques	3
A01K	Animal husbandry; care of birds, fishes, insects; fishing; rearing or breeding animals, not otherwise provided for; new breeds of animals	6
A01N	Preservation of bodies of humans or animals or plants or parts thereof; biocides, e.g. as disinfectants, as pesticides or as herbicides; pest repellants or attractants; plant growth regulators	7
A61K	Preparations for medical, dental or toilet purposes	10
A61P	Therapeutic activity of chemical compounds or medicinal preparations	4
A23	Foods or foodstuffs; their treatment, not covered by other classes	6
B01D	Separation	6
C02F	Treatment of water, waste water, sewage or sludge	2
CO7D	Heterocyclic compounds	2
C12N	Micro-organisms or enzymes; compositions thereof; propagating, preserving, or maintaining micro-organisms; mutation or genetic engineering; culture media	35
C12Q	Measuring or testing processes involving enzymes or micro-organisms; compositions or test papers therefore; processes of preparing such compositions; condition-responsive control in microbiological or enzymological processes	3
G01N	Measuring; testing	3

Total set of 912 patent records; data set for analysis limited to categories with more than 20 records; totaling to 87%.

evidence on possible risks on the environment, health and impacts on the social structure considering the broad areas it can affect.

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