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Integrating nanotechnology into agri-food systems research in India: A conceptual framework

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ABSTRACT

The implications of current trends in nanotechnology for the agri-food sector in India are assessed. Using published literature and patents data, a model to organize the information is developed through a specially designed database. The database allows mapping research themes in nanotechnology to specific sectors in the agricultural value chain to enable a rational assessment of the potential applications of nanotechnology in the agri-food sector, identifying and prioritizing research needs across the agricultural value chain, and assessing the environmental and societal implications of this emerging technology.

1. Introduction

Nanotechnology is the "understanding and control of matter at dimensions of roughly 1 to 100 nm", where unique phenomena enable novel applications [1]. The application of nanotechnology (NT) to the agricultural and food industries was first addressed by the United States Department of Agriculture in its roadmap published in September 2003 [2]. It is now emerging as a rapidly evolving field with a potential to revolutionize agriculture and food systems [3], across the entire agricultural value chain [4,5]. In India too, nanotechnology is beginning to be seen as an important option for enhancing agricultural productivity, along with other emerging technologies such as biotechnology, to complement conventional agricultural technologies [6,7]. However, to make an impact on the rural economy, it is important to recognize that this new technology needs to be extended beyond the farm to all the links across the entire agricultural value chain. The key role of this technology is also envisaged in agri biotechnology in the areas of gene delivery, gene expressions, gene sequencing, gene therapy, gene regulation, DNA targeting, DNA extraction, DNA hybridization, fingerprints for DNA and RNA detection, cell probes, specific targeting, cell sorting and bioimaging, single-cell-based assay, drug delivery, tissue engineering, proteomics and nanobiogenomics.

Investments in nanotechnology are also important to ensure that India's National Agricultural Research System (NARS) stays globally competitive. The need to maintain technological parity with global competitors is a critical strategic issue for the nation's agricultural and rural sectors. Emerging technologies like nanotechnology, which can enhance technological outputs and also benefit rural communities, will then become more acceptable. However, this is possible only if a more coherent system approach is adopted for planning technology development and implementation across the agricultural supply chains. This will help to assess where innovation can contribute to competitive advantage and identify commercial partners who can adopt and benefit from new

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technologies, and assist with their implementation. These need to be identified early and actively pursued in national developmental plans.

The objective of this study is to develop a general process based framework and methodology for a systematic assessment of the potential for the application of nanotechnology across the various links in the agricultural value chain. Such a framework would lead to a roadmap for integrating nanotechnology into agri-food systems research in India, and help prioritize research investments for relevance, global competitiveness and quick impact. A key purpose is also to anticipate environmental and societal consequences so that necessary regulatory mechanisms to ensure that some of the difficulties encountered in introducing new technologies in agriculture (as for GM crops) can be anticipated and avoided or overcome.

2. Framework and methodology

The proposed framework and methodology for integrating nanotechnology research in agri-food systems is based on technology roadmapping and database management concepts. The technology roadmapping process takes into account both the nature of the emerging technologies as well as the scenario for technology generation, dissemination and transfer. Further, it attempts to map nanoresearch areas to the research themes along the agricultural supply chain, that is, the entire production–consumption system (Fig. 1).

It is emphasized that the implications of nanotechnology research for agriculture need to be assessed not only at the farm production system level, but also beyond the farm gate, and encompassing all the links across the entire agricultural value chain: farm inputs, farm production systems, post harvest management and processing and value addition, and finally to the markets and consumers. A variety of private and public institutions that provide the various services along the agricultural supply chain also need to be included in the technology development and transfer processes. Therefore, if the goal is to ensure that nanotechnology based interventions add value to agriculture, they should be at the various links of the supply chain to increase productivity and quality at the farm level; decrease costs and enhance product life during storage and transportation; improve efficiencies and quality of processing and generate new products; improve efficiencies and product shelf life and quality in marketing and distribution; and increasing consumer acceptance.

The framework is developed in five steps:

(i) identification of nanoresearch and agri-food thematic areas
(ii) relating nanoresearch areas with the agri-food thematic areas
(iii) designing the database structure for bibliographic and patents data storage and analysis
(iv) designing the bibliographic search strategy
(v) designing a patent search strategy.

2.1. Step 1: identification of nanoresearch and agri-food research thematic areas

The identification of nanoresearch and agricultural research thematic areas of relevance to agri-food systems in India was done based on:

(i) a preliminary survey and assessment of literature
(ii) interviews with leading experts in Cornell University, USDA, National Nanotechnology Initiative (NNI), and other centers in USA
(iii) data collected from surveys with researchers in the National Agricultural Research System (NARS) in India.

The nanoresearch areas and agricultural research areas likely to contribute to more sustainable production in agri-food systems in India were thus identified and are given in Tables 1 and 2.

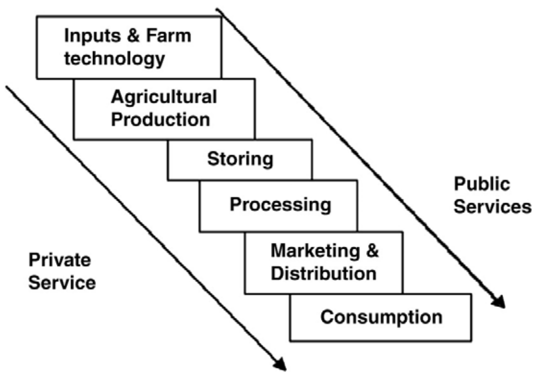

Fig. 1. The agricultural supply chain.

Table 1
Nanoresearch thematic areas of relevance to agri-food systems in India.

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

Table 2
Key agri-food thematic areas where nanotechnology has potential application.

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

2.2. Step 2: relating nanotechnology research areas to agri-food thematic areas

The life cycle of new and emerging technologies like nanotechnology typically progresses through identifiable patterns of scientific, technological and economic developments. There is a time lag between the three different stages and usually, the scientific push will precede the technology pull and market pull. Therefore, as part of the next step, the Research and Development (R&D) outputs of nanotechnology were assessed and quantified by publications (for scientific performance), patents (for technological performance), and products in the market (for commercial presence). A generalized and process based framework (Fig. 2) to enable identification and characterization of the outputs (publications, patents etc.), and map them to the different agricultural research theme areas through the filter of links in the agri-value chain was developed. The framework also permits assessing the implications for technology transfer, and impacts on society and environment.

2.3. Step 3: designing the database structure for bibliographic and patents data storage and analysis

The database structure was designed to facilitate the mapping process — that is mapping nanotechnology patents and publications to the agricultural research thematic areas identified above (Tables 1 and 2 and Fig. 1). Literature and patents accessed on the basis of carefully chosen search strings were scanned carefully, assessed for their implications with respect to the agri-food thematic areas, and entered in the database. Both bibliographic and patent databases were developed independently in MS Access. The database environment allows querying, analysis and mapping the technology trends independently by the key factors of relevance, namely: nanotechnology area, supply chain sector, agricultural research area, possible health and environmental risks, and social implications (Tables 3 and 4). The publications and patents are also made accessible from a digital library created for this purpose from the database tables.

2.4. Step 4: designing the bibliographic search strategy

Research publications were of different types, research papers, research reports, review papers, news articles, reports, perspectives, website reviews, letters, commentary, conference papers and chapters in books. They were collected by conducting a keyword search on paper titles; keywords and abstracts using a list of strategically selected agriculture nanotechnology keywords. Nanoresearch publications were identified initially as Science Citation Index (SCI) records from Web of Knowledge.[2] This was followed with publications from several public domain online resources. The publications included research papers, news articles, reports, other academic literature and industry relevant publications. Websites of commercial publishers, who have made their online content available on their web, were also utilized. Full text of the publications available from Springer, Nanotechnology, Nature Nanotechnology, Journal of Nanobiotechnology, Current Science, Journal of Nanoparticle Research, Technology Forecasting and Social Change, NanoEthics, Nanoscale Research Letter, either through PubMed, CeRA (Consortium for e-Resources in Agriculture) also formed part of resources. Thus the attempt was to use various resources ranging from formal to informal

[2] Initial part of the study was conducted at Cornell University through a Fulbright research grant awarded to one of the investigators of the project team.

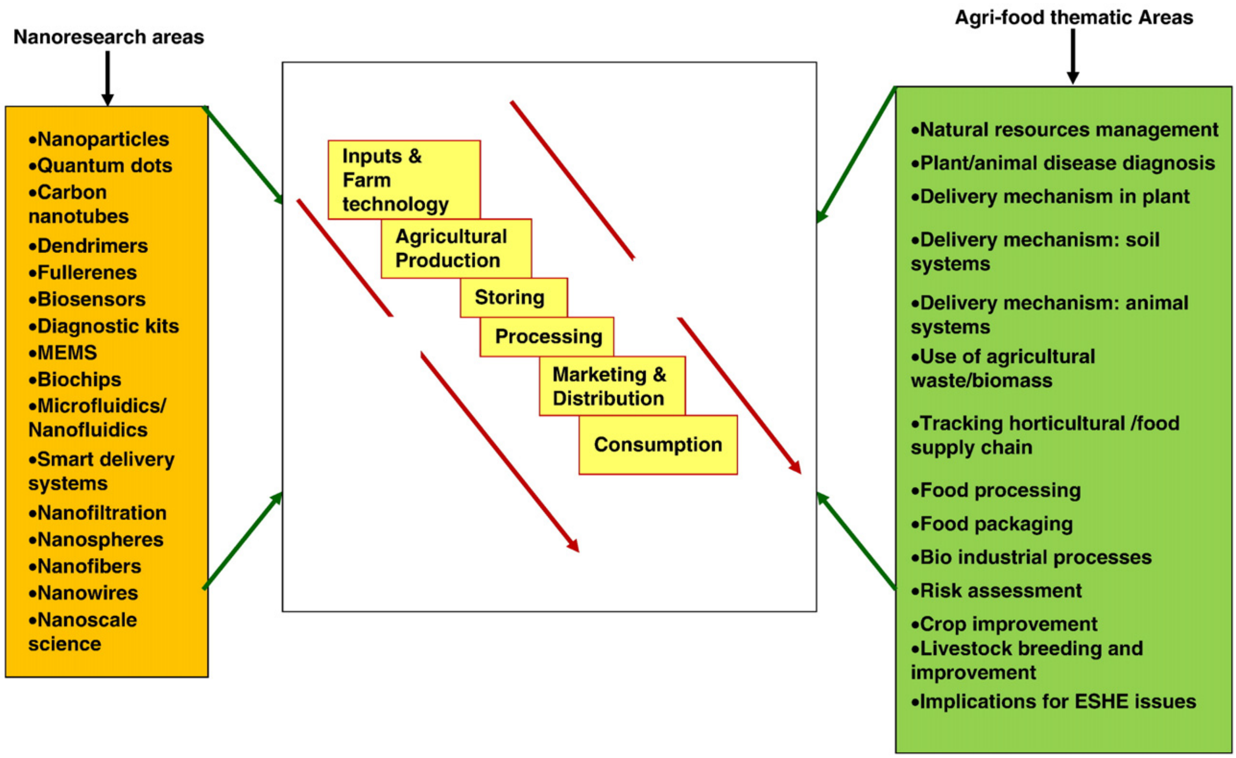

Fig. 2. Framework for integrating nanoresearch and agri-food thematic areas.

publications and covering disparate sources that included text based to multi-media presentations, academic literature to industry reports, websites, chat rooms and other diverse sources.

2.5. Step 5: designing a patent search strategy

Patents related to specific agriculture domain were collected from three resources namely: freely available databases of international/national patent offices[3]; no charge providers[4] and charge providers[5]. Parsing was done to obtain relevant set of patents of individual agriculture thematic areas with reference to corresponding IPC, USPTO and EPO codes. A set of subject specific keywords and standardized search strings was identified by domain experts and was used to perform full text search of patents (patent titles, abstract, claims and descriptions). Resulting patents were reduced to one patent per family. Duplicates were removed and temporary work sheets were exported in CSV format. After removing repeats, individual patents were later analyzed to estimate whether they are truly nanotechnology related patents.

Patents that showed 'incidental noises' of nano like $NaNo_3$ (sodium nitrate), nanometer, nanolitre, nanosecond, nanospectrometer and others were removed (Fig. 3). This process for searching for valid patents was repeated in all the prioritized agricultural thematic areas identified. Units of analysis and representations include inventors, type of affiliations, country, and citation network of patents, nanoresearch area, technology field and timelines. The nanotechnology related agri patents were then linked to the agriculture value chain and nano research areas. Fig. 4 presents the final flowchart of the entire process.

For both bibliographic and patent sources, the assessment was carried out with respect to the following:

(i) nanotechnology product (nanoparticles, nanotubes, quantum dots, etc.) and its characteristics
(ii) agricultural supply chain sector affected
(iii) possible social and environmental risks
(iv) time to commercialization
(v) inventors and their location
(vi) other factors.[6]

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[3] United States Patent and Trademark Office (USPTO), European Patent Office (EPO), World Intellectual Property Organization (WIPO) and Indian Patent Office (IPO).

[4] Cambia, Google patents, FreePatentsOnline.

[5] Technology Information, Forecasting and Assessment Council (TIFAC) for Indian patents, and Micropat (PaT web service offered by Thomson Reuters).

[6] In bibliographic database: publication year, funding sources, cost of the nano research projects, duration of the research, multinational collaborations and research requirements; in patents database: publication year, priority year, patent document kind, IPC classes, assignee/applicant of the patent, patent citations, and legal status of the patent.

Table 3
Fields in the publications databases.

Field name	Data type	Description
RID	Number	Identification number
Type	Text	Research project/paper/report
Investigators	Text	
Year	Number	Year of publication
Title	Text	Project/paper/report, etc
Reference	Memo	Complete bibliographic reference
Institute	Text	
Country	Text	
Multinational	Yes/no	Collaborations
Cost	Text	
Funding sources	Text	
Duration	Text	Dates, timeline of research
Abstract	Text	
Objective	Text	
Keyword 1	Text	Keywords are selected based on the nanoresearch and agri-food theme areas
Keyword 2	Text	
Keyword 3	Text	
Keyword 4	Text	
Keyword 5	Text	
Additional information	Text	
Sector of supply chain (SID)	Number	Fig. 1
Nano research area (NAID)	Number	Table 2
Agriculture thematic area (Theme ID)	Number	Table 2
Possible applications (AID)	Number	Based on the assessment of the paper
Environment risks	Yes/no	
Social risks	Yes/no	
Health risks	Yes/no	
Environment benefits	Yes/no	
Social benefits	Yes/no	
Health benefits	Yes/no	
Exposure end points	Text	Scientists, workers, farmers, animals
Research requirements	Text	Infrastructure, instruments, consumables
Time to commercialization	Text	0–5 yrs, 5–10 yrs, 10–15 yrs, 15–20 yrs
IP issues	Text	FTO issues etc.
Comments	Text	
Hyperlink	Hyperlink	To original source if available
Digital library	Hyperlink	Link to files of publications in MS word, pdf, web page formats in the database

3. Generalized output of bibliographic and patent databases

Using the process indicated above, two databases were developed;

1. bibliographic database (from 500 sources)
2. patent database (1000 patents).

The results of querying, accessing and text mining of the records from these databases (Table 5) clearly demonstrate the multi-faceted nature of applications of nanotechnology and indicate the promise these hold in the 12 identified areas across the agriculture value chain for Indian agri-food systems. Detailed analysis of data in each of these areas can help to assess and identify relevant research tools, which can be integrated into the application.

4. Application

4.1. Assessing biosynthesis as an eco-friendly pathway for the synthesis of nanoparticles

An essential pre-requisite for the integrating nanoresearch into the agri-food chain is the synthesis of the source nanomaterials, the most widely used among them being nanoparticles. Nanoparticles of different chemical compositions, sizes and controlled monodispersity need to be produced in large quantities for agricultural applications. Many of the popular modes of synthesis of nanoparticles rely on toxic chemicals and synthesis protocols. An important aspect, particularly from the agricultural perspective, is the availability of eco-friendly modes of synthesis of nanoparticles. An independent search of the available literature and patent database was carried out to identify methods for environmentally benign synthesis of nanoparticles.

The analysis showed that several researchers in the field of nanoparticle synthesis and assembly have turned to the use of biological systems, where micro organisms (bacteria, yeasts, algae, fungi and actinomycetes), agricultural residues and biomass and plant mediated processes are used. Several research groups are active in the biosynthesis of nanoparticles independently or through group or country level collaborations. The search results indicate that this activity is in progress in nearly 12 countries,

Table 4
Fields in the patents databases.

Field name	Data type	Description
IPC code	Text	International patent classification code to which the patent belongs
Patent/publication no.	Text	Unique identification number assigned to each patent after it has been published
Country code	Text	Indicating the country or organization where the patent application was filed or granted
Document kind	Text	Code indicating the version or level of examination of a patent document. Kind codes and their meanings are country specific
Publication year	Number	Year of publication
Date of publication	Number	Date of publication
Application date	Number	Date when a complete application was received by the patent office
Application no.	Text	Identification number assigned by the patent office to applications, which have received a filing date
US class (primary)	Text	USPTO classification — primary class only
US classes (all)	Text	USPTO classification — primary class and any other listings as secondary listings
International class (primary)	Text	International classification system, which is not used in the US
IPC classes	Text	International classification(s) to which the patent has been assigned
ECLA	Text	Classification scheme assigned by the European patent office to patent documents in order to facilitate prior art searches
Assignee/applicant	Text	Name of the individual or entity to whom ownership of the patent was assigned at the time of patent issue
Inventor (first only)	Text	Inventor of patented item
Inventor(s)	Text	Inventors of patented item
Priority year(s)	Number	Period, during which the priority right exists, is usually 12 months for patents. This period of priority is referred as the priority year.
Priority date	Number	
Priority country	Text	The country in which the earliest filing of a patent application is claimed.
Patent citations	Text	Citations of the patents which have forward citation and backward citation
Title of the patent	Text	Title of the patent
Abstract	Text	Contains a concise summary of the disclosure of the invention as contained in the description, claims and drawings
Family members	Text	Other patents which belong to the same family of the referred patent
Legal status	Text	Legal status of patents
Nanotechnology applied	Text	Nanotechnology
Type	Text	Ground on which the patent has been claimed for
Country/family members	Text	List of countries from where all the patent family members belong
Objectives	Text	
Keyword 1	Text	Keywords are selected based on the nanoresearch and agri-food theme areas
Keyword 2	Text	
Keyword 3	Text	
Keyword 4	Text	
Keyword 5	Text	
Additional information	Text	
Sector of supply chain (SID)	Number	Fig. 1
Nano research area (NAID)	Number	Table 2
Agriculture thematic area (Theme ID)	Number	Table 2
Possible applications (AID)	Number	Based on the assessment of the paper
IP issues	Text	Either patent is granted/application phase/abandoned/expired
Hyperlink	Hyperlink	To original source if available
Digital library	Hyperlink	Link to downloaded files of patents in MS word, pdf, web page formats in the database

USA, Iran, China, Iran, Mexico, Brazil, Canada, New Zealand, Israel, Singapore, Korea, Denmark, New Zealand, UK France, Mexico and India. 37% of publications out of the 500 records are research groups based in India working on developing protocols for the extraction and synthesis of nanoparticles from biological resources. Table 6 gives list of Indian institutes involved in the

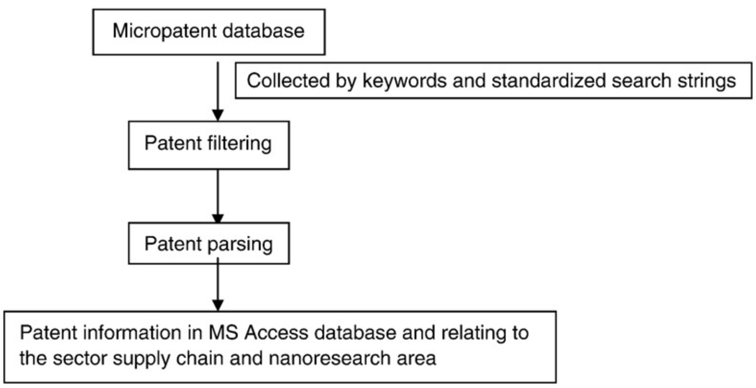

Fig. 3. Methodology patent data acquisition and analysis.

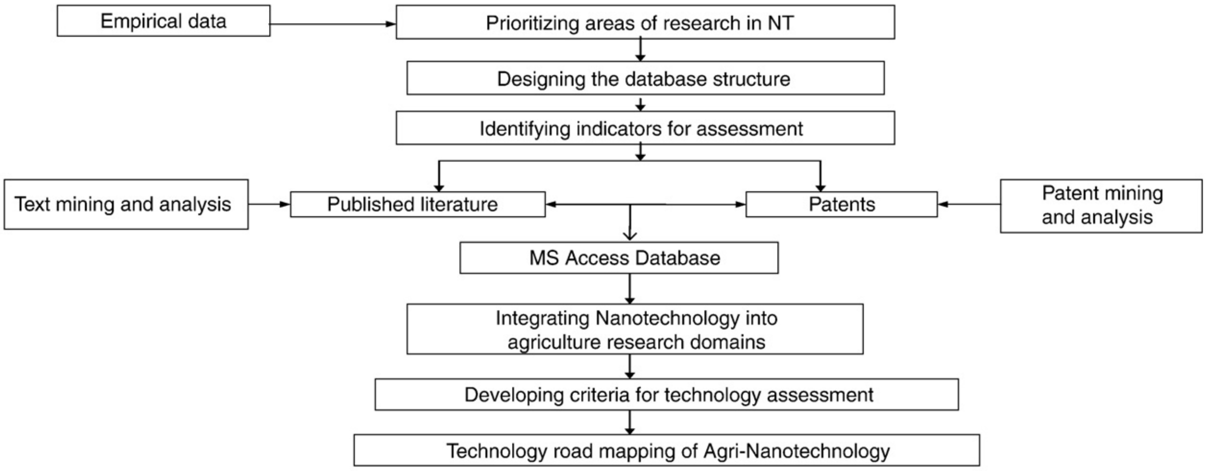

Fig. 4. Methodology for the development of technology roadmap for nanotechnology in agriculture.

nanoparticle biosynthesis with the details of their research work, funding source for their projects as well their publication information.

A point to note is that most of the above research is at the protocol development stage and will need to be extended to the application stage to be transformed to technology level. It is well known that Indian agriculture-food systems are among the most intensive sectors when compared to farming in temperate regions of the world. Keeping in view the need for environmentally friendly processes for synthesis, of nanoparticles, the relatively high level of expertise available in this area in India, and the availability of basic biomaterial for such synthesis, biosynthetic pathways can be identified as a priority area for research investments in agri-food nanotechnology. Such a model can lead to more environmentally and socially acceptable technologies that can be extended across the agricultural supply chain. Since India appears to have a competitive advantage in research in this area, a convergence of the agriculture researchers and synthesizers of nanoparticles would be a viable option to be explored by policy makers for developing an agri-food vision for nanotechnology.

4.2. Risk assessment of nanotechnology

As with any new technology that offers significant benefits to humankind, there are also risks of adverse and unintended consequences with nanotechnology. An analysis of literature in the database indicated possible and perceived risks using NT, which were categorized into 3 types namely, environmental risks, social risks and health risks. Only 18% of publications referred to nanotechnology induced risks, with health risk (24%) as the major risk. The risk is due to small size and large surface area of nanoparticles, which allow easy dispersion, and bonding with human tissues. In the agriculture sector, handling of nano fertilizers and pesticides by millions of small farmers can prove to be a leading health risk.

Possible environmental risks were indicated in 23% of the papers. These risks can be caused by fertilizers and pesticides enhanced with nanomaterials that allow easy dispersal into the soil, water, or atmosphere. The risk can be attributed to the known fact that nanoparticles bond more strongly with pollutants and transport them through soil and water.

Adverse impacts of high cost technologies on livelihoods, restrictions on access to technologies as most research is in private sector and subject to intellectual property protection, job insecurity, and imbalance across geographical areas and national security were identified as possible social risks. Only 16% of publications referred to possible risks at these levels. Involving the stakeholders in the early stage of technology development so that they are aware of the possible risks and uncertainties associated with the new technologies can lead to better understanding and acceptance of the products coming from the research as well as alert nanoresearchers and policy makers to risk assessment before commercialization of nanotechnology products.

5. Conclusion

1. A database technology-based process methodology to search, assemble and characterize available bibliographic and patent information in nanoresearch areas and map them to the identified agricultural research thematic areas across the agricultural value chain was developed.
2. The database allows for mining information in specific areas of application of nanotechnology in agriculture, and for a transferable process for assessing its environmental, ethical, legal and societal implications.
3. The nanotechnology innovation cycle in agri-food systems is special as it is largely an enabling technology that seeks to improve the functionality of existing products at each link in the agricultural value chain. It is obvious that routine independent and isolated funding of public or private research in nanotechnology cannot lead to its successful application.

Table 5
Agri-food thematic areas and corresponding nanoresearch areas and applications.

SN	Agri-food thematic areas	Nanoresearch area and possible applications
1	Natural resource management — efficient use of soil resources	▪ Nanoparticles — soil in situ remediation, absorption and release of contaminants in soil ▪ Nanoscale iron particles — rapid destruction of chlorinated hydrocarbons in soil and groundwater ▪ Nanosensors — continuous monitoring of heavy metals
	Natural resource management — efficient use of water resources	▪ Nanotechnology — desalination and water purification ▪ Nanoporous membranes — filtration of viruses ▪ Nano-sponges — absorb toxic metals ▪ Ozone nano-bubbles — sterilize water ▪ Nanowire immunosensors array — detects microbial pathogens ▪ High piezoelectric PMN-PT microcantilevers — ultrasensitive pathogen quantification in drinking water
	Natural resource management — efficient use of energy resources	▪ Nanomaterials — used in lithium-ion rechargeable batteries ▪ Plasmon sensitized TiO_2 nanoparticles — novel photo catalyst for solar applications ▪ Polymer nanotube composite — photovoltaic packaging applications in energy sector ▪ Ecocomposites reinforced with cellulose nanoparticles — alternative to existing petroleum-based polymer composites ▪ Nanomaterials — extract energy from the environment to generate electrical power for sensors and other devices ▪ Silicon nanowire battery electrodes — accommodate large strain without pulverization, provide good electronic contact, conduction and display short lithium insertion distances
2	Plant/animal disease diagnostics	▪ Nanotechnology implemented within current diagnostic equipment has the potential of analyzing the entire genome in minutes instead of hours ▪ Nanobarcodes are ID tags for multiplexed analysis for gene expression and intracellular histopathology ▪ Quantum dots are fluorescence marker coupled with immunomagnetic separation that detects *E. coli*. QD is useful in antimicrobial photodynamic therapy ▪ Label-free sensor chip assembled from peptide nanotubes — electrical detection of viruses with extremely low detection limit ▪ Sensor array containing 6 non-covalent gold nanoparticles fluorescent polymer conjugates — detects, identifies and quantifies protein targets
3	Delivery mechanisms in plant, soil and animal systems	▪ Mesoporous silica nanoparticles — deliver DNA and chemicals into plants ▪ Smart magnetic silica core–shell nanomaterials — specific targeting, cell sorting and bioimaging ▪ Nanocontainers — deliver drugs to organs or tissues ▪ Organically modified silica nanoparticles — act as DNA carriers, which is a nonviral, nanomedicine approach for gene delivery ▪ Carbon nanofibres — gene therapy of plants ▪ Nanoelectrode gaps — help in single-strand DNA molecule translocation ▪ Oligonucleotide-loaded nanoparticles — enhance the expression of rice α-galactosidase gene in yeast cells ▪ Micro/nanofluidic device — single-cell-based assay ▪ Carbon nanotubes — molecular transporters ▪ Silicalite nanoparticles — promote transgene expression
4	Use of agricultural waste/biomass	▪ Biosynthesis of nanoparticles by microbes such as fungi, bacteria, viruses and actinomycetes ▪ Plant-mediated synthesis of nanoparticles ▪ Biosynthesis of nanoparticles by the utilization of agriculture residues — wheat straw, soy hulls, rice hull, *Avena sativa* biomass, and natural fibers
5	Tracking the horticultural/ food value chain	▪ Nanoparticle based biobar codes — ultrasensitive detection of proteins ▪ Micro fluidic chip — probes living cells ▪ Magnetic nanoparticles — remote controls cellular behavior ▪ Nanoparticles with Raman spectroscopic fingerprints — detect DNA and RNA ▪ Silica nanofiber membranes — protein detection ▪ Tin oxide nanowires — water vapor detection
6	Food processing	▪ Nanotechnology in food safety and quality control and in the production of functional and nutritive foods ▪ Quick detection of food borne pathogens using bioconjugated nanomaterials, biosensor, nanocantilevers, carbon nanotubes, nanowires, and BioMEMS
7	Food packaging	▪ Natural biopolymer-based nanocomposite films are used for food packaging for safe storage ▪ Edible nanosensors may indicate bacterial contamination in the packaged foods ▪ Nanoscale titanium dioxide particles blocks UV light in plastic packaging
8	Bio-industrial processes	▪ Electro spinning technique offers a time and cost effective production of strategic combinations of polymer and composites nanofibers useful for numerous applications ▪ One-step purification of lectins from banana pulp using sugar-immobilized gold nanoparticles ▪ Organic-phase synthesis method for producing size-controlled, nearly monodispersed, colloidal uranium-dioxide nanocrystals
9	Risk assessment/safety	▪ Life cycle assessment in nanotechnology ▪ Nanotoxicity — assesses threat posed by nanoparticles and nanomaterials ▪ Risk management models for regulating nanotechnology ▪ Nanosensors — detection of aquatic toxins
10	Developing new genetic types/ breeds/cultivars and crop production	▪ Atomically modified rice by drilling a nano-sized hole through the wall and membrane of a rice cell in order to insert a nitrogen atom ▪ Functionalized CPMV nanostructures can be stored for a long term, enabling their use in practical sensing applications ▪ Magnetic nanoparticles coated with tetramethylammonium hydroxide influence the growth of *Zea mays* plants in early ontogenetic stages.

Table 5 (*continued*)

SN	Agri-food thematic areas	Nanoresearch area and possible applications
		▪ Carbon nanotubes are crucial chemical ingredient that could make artificial photosynthesis possible ▪ Blue shift of CdSe/ZnS nanocrystal — labels upon DNA hybridization. ▪ Alumina nanoparticles slow down the growth in plants
11	Livestock breeding and livestock management	▪ Studies to measure the responses of fish to a dietary exposure to two types of nanoparticles, carbon nanotubes and titanium dioxide ▪ Veterinary medicines — composition of nanoparticles, nanocapsules and nanospheres ▪ Smart treatment delivery system — a miniature device implanted in an animal that samples saliva on a regular basis. Before a fever develops, the integrated sensing, monitoring and controlling system could detect the presence of disease and notify the farmer and veterinarian to activate a targeted treatment delivery system
12	Ethical, social, legal, environmental implications	▪ Societal transformation and societal issues of nanotechnology ▪ Public acceptance and awareness about nanotechnology ▪ Nanoethics and environmental implications of nanomaterials

4. A higher-level integration in the innovation cycle through public and private partnerships, and innovative use and integration of existing knowledge and technologies in agriculture with nanotechnology is imperative from the initial stages itself. Innovative partnerships between agricultural research institutions, with basic science institutions with strengths in nanosciences for the design of the nanomaterials, and with nanotech companies for the design and production of the nanomaterials would lead to quicker impacts of nanotechnology in agri-food systems.

Table 6
List of institutes involved in nanoparticle biosynthesis research in India.

Institutes of research team	Publication year	Type of publication	Type of work		Funding source
			Synthesized particle	Bio-resources	
NCL, Pune	2003	Research paper [8]	Silver nanoparticles Gold nanoparticles	*Verticillium* sp. Actinomycete–*Thermomonospora* sp.	
	2005	Research paper [9]	Gold, silver and their alloy nanoparticles	Bovine serum albumin	DST
	2005	Research paper [10]	Bimetallic Au–Ag alloy nanoparticles	*Fusarium oxysporum*	CSIR and DBT
	2004	Research paper [11]	Zirconia nanoparticles	*Fusarium oxysporum*	
	2003	Research paper [12]	Silver nanoparticles	Geranium leaf assisted	
	2004	Research paper [13]	Au, Ag, and bimetallic Au core–Ag shell nanoparticles	Neem (*Azadirachta indica*) leaf broth	CSIR
NCL, Saha Institute of Nuclear Physics and BARC, Mumbai [a]	2006	Research paper [14]	Nanoparticulate magnetite	*Fusarium oxysporum* and *Verticillium* sp.	CSIR and DST
NCL, Armed Forces Medical College, Pune and CIMAP, Lucknow [a]	2001	Research paper [15]	Gold nanoparticles	*Verticillium* sp.	CSIR
University of Pune and NCL [a]	2008	Research paper [16]	Crystalline silver nanoparticles	*Morganella* sp.	DST and DBT
Institute of Himalayan Bioresource Technology, Palampur	2008	Review paper [17]	Nanoparticles	Microorganisms and plants	CSIR
	2008	Mini review [18]	Silver and gold nanoparticles	Plant-mediated	
Gulbarga University, Karnataka	2008	Research paper [19]	Silver nanoparticles	*Fusarium semitectum*	UGC
	2008	Research paper [20]	Au and Au–Ag alloy nanoparticles	*Fusarium semitectum*	UGC, DST
BARC, Mumbai and Institute of Physics, Bhubaneswar [a]	2008	Research paper [21]	Nanocrystalline silver particles	*Trichoderma asperellum*	
Guru Gobind Singh Indraprastha University, Delhi	2005	Review paper [22]	Nanomaterials and nanoparticles	Microorganisms	
Basaveshwar Engineering College, Bagalkot and Karnataka University, Dharwad	2007	Review paper [23]	Awareness creation on biosynthesis of nanoparticles		
Bharathidasan University, Tiruchirappalli and Vivekananda Institutions, Thiruchengode [a]	2008	Research paper [24]	Silver nanoparticles	*Helianthus annus*	
Pondicherry University	2008	Research paper [25]	Gold nanoparticles	Coriander leaf-mediated	
Thiruvalluvar University, Vellore and Sathyabama University, Chennai [a]	2008	Research paper [26]	Mettalic silver, gold and Au core/Ag shell nanoparticles	*Spirulina platensis*	
SGB Amravati University, Maharashtra	2009	Research paper [27]	Silver nanoparticles	Callus extract of *Carica papaya*	

[a] Institutes working in collaboration.

All of these point to the need for a change in institutional policies and systems within the National Agricultural Research System, for integrating nanotechnology into agri-food systems research.

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