Research Review Article

Indian Journal of Agricultural Sciences **81** (10): 887–93, October 2011

Prospects of nanotechnology in Indian farming

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Received: 17 May 2010; Revised accepted: 12 May 2011

ABSTRACT

Nanotechnology is an emerging field of science widely exploited in electronics, energy, environment and health sectors. Indeed, nanotechnology applications in agriculture is rarely studied in India and abroad. But many research organizations and universities have begun to invest in order to gain solutions to unresolved field poblems. The Tamil Nadu Agricultural University, Coimbatore, is one of the early birds in such endeavours to initiate research in the fascinating field of science. The reported literatures across the globe suggest potentials of nanotechnology applications in biological sciences including agriculture. In this review, applications of nanotechnology in agricultural sciences such as nano-agricultural inputs, nano-food systems, nano-biotechnology and nano-remediation have been summarized.

Key words: Nanofertilizer, Nanoherbicides, Biosensors, Smart delivery system, Precision farming

Nanotechnology is a field of convergence among life sciences, material science and information technology. It is an emerging field of science capable of resolving issues and problems that are impossible to tackle in engineering and biological sciences. Nanoscience and technology involve studying and working with matter on an ultra-small scale that allow us to work, manipulate and create tools, materials and structures at the molecular level, often atom by atom into functional structures having nanometer dimensions. One nanometre is one-millionth of a millimetre and a single human hair is around 80 000 nanometres in width. Simply if the entire Indian population (1.04 billion) is squeezed to a 1 m length, each Indian is considered as a nano-particle. Among the many advancements in science, nanotechnology is being visualized as a rapidly evolving field that has potential to revolutionize agriculture and food systems (Roco 2003, Kuzma and Verltage 2006, Abdul Kalam 2007, Lal 2008), and improve the condition of the poor (Juma and Yee-Cheong 2005). Despite the fact that nanotechnology served as a prime tool to develop several products in material science, medicine and defense, we begin to scratch the surface in the field of agriculture.

GLOBAL SCENARIO

The global nanotechnology market is expected to touch US $29 billion mark by 2010. The exponential growth of global investment in nanotechnology research closely coincides with the number of patents relating to nano-products. Recent statistics suggests that 88% of the patents is generated from just seven countries comprising US, China, Germany, France, South Korea, Switzerland and Japan. India's investment is far from the global club of nanotechnology. In 2008, both public and private sectors worldwide had invested about US $20 billion. Market forecasts indicate US $1 880 billion investments on nanotechnology related sales across all sectors by 2015.

INDIAN SCENARIO

The Department of Science and Technology (DST) launched the Nano Science and Technology Initiative (NSTI) in 2001 under the leadership of Prof. C N R Rao. The NSTI has been focusing on research and development in nanoscience and technology in a comprehensive manner so that India can become a significant player in the area and contribute to the development of new technologies, besides carrying out basic research at the frontiers of knowledge. The Government of India is currently spending ₹1 000 crores under Nano Science and Technology Mission (Nano Mission) during the Eleventh Five-year Plan period. The activities of Nano Mission encompass launching of a variety of educational and HRD programmes, R&D programmes, establishing centres of excellence, promoting institution-industry linked projects through increased public-private partnerships, facilitating entrepreneurship through establishment of business incubators, etc. The Nano Mission also plans to make special efforts for development and

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commercialization of nanotechnology, not only through public-private partnerships but also by encouraging and enabling the private sector to invest in, and leverage this sunrise technology. The investment on biological sciences including agriculture is less than 5% and therefore lots of scope available for agricultural scientists to exploit the fascinating technology. Within the sphere of agricultural sciences, nanotechnology application in relation to soil and crop management is in its nascent stage and over the next few years it is expected to grow exponentially.

NANOTECHNOLOGY IN INDIAN AGRICULTURE

The Indian Government is looking towards nanotechnology as a means of boosting agricultural productivity in the country. Recently, the Planning Commission of India recommended nanotechnology research and development (R&D) as one of six areas for investment. The Commission recommended policies and carries out financial planning for government departments. The report was written by a subgroup of the Commission, and incorporated into India's Eleventh Five-year Plan, for 2007–2012. In order to harness the benefits of nanotechnology, biotechnology and bioinformatics to transform Indian agriculture, an exclusive National Institute of Nanotechnology in Agriculture has to be established. The report says nanotechnology such as nano-sensors and nano-based smart delivery systems could help ensure natural resources such as water, nutrients and chemicals are used efficiently in agriculture. Nano-barcodes and nano-processing could also help monitor the quality of agricultural produce. The report proposes a national consortium on nanotechnology R&D to include the proposed national institute and Indian institutions that are already actively researching nanotechnology. It also recommended that Indian universities and institutions develop suitable graduate and postgraduate programmes to train young scientists in nanotechnology.

If Indian agriculture is to attain its broad national goal of sustainable agriculture growth of over 4%, it is important that the nanotechnology research is extended to the agricultural total production – consumption system, that is, across the entire agricultural value chain. This would require focusing on technologies that increase agricultural productivities, product quality and resource-use efficiencies that reduce on-farm costs, raise the value of production, and increase farm income; as well as on conserving and enhancing the quality of the natural resource base. It would also require a conscientious effort to provide a system to deliver these innovations based on nanotechnology to a product delivery stage and ensure that these reach the rural stakeholders at the end of the agri-value chain.

WHY SHOULD AGRICULTURAL SCIENTISTS THINK OF NANOTECHNOLOGY?

Agricultural scientists are facing a wide spectrum of challenges in crop production system such as crop yield stagnation, declining organic matter, multi-nutrient deficiencies, climate change, shrinking arable land and water availability, resistance to GMOs and shortage of labour.

- Indian agriculture feels the pain of fatigue of green revolution. In the past 50 years, the fertilizer consumption exponentially increased from 0.5 (1960's) to 23 million tonnes (2008) that commensurate with four-fold increase in foodgrain output (234 million tonnes). Despite the resounding success in grain growth, it has been observed that yields of many crops have begun to stagnate as a consequence of imbalanced fertilization and decline in organic matter content of soils.
- The optimal NPK fertilizer ratio of 4:2:1 is ideal for crop productivity while the current ratio is being maintained at 10: 2.7: 1 in India. nitrogenous fertilizers, particularly urea is heavily subsidized by the government and thus its application is more obvious than other nutrients. Excessive N fertilizer-use affects groundwater and also causes eutrophication in aquatic ecosystems. The imbalanced fertilization is considered a serious concern rapidlly deteriorating the soil health.
- The fertilizer response ratio in the irrigated areas of the country has dcreased from 13.4 kg grain / kg nutrient applied in 1970's to just 3.7 kg in 2005. In other words, more amounts of fertilizers is required to produce the same quantity of grain output. For instance, 27 kg NPK/ha was required to produce one tonne of grain in 1970 while the same level of production can be achieved by 109 kg NPK/ha in 2008 (Biswas and Sharma 2008).
- In order to achieve a target of 300 million tonnes of food grains and to feed the burgeoning population of 1.4 billion in 2025, the country will require 45 million tonnes of nutrients as against a current consumption level of 23 million tonnes. The extent of multi-nutrient deficiencies are alarmingly increasing year by year which is closely associated with a crop loss of nearly 25–30%. The extent of nutrient deficiencies in the country are in the order of 89, 80, 50, 41, 49 and 33% for N, P, K, S, Zn and B, respectively. The data from long-term fertilizer experiments unequivocally demonstrated that conjunctive use of organic and inorganic is essential to sustain soil health. But the availability of organic manures is becoming scarce as a result of urbanization and reduction in animal wealth.
- Climate change is yet another serious concern. Eratic rainfall, frequent occurence of drought, melting polar ice cap, temperature rise (0.4 to 4.0ºC in the past century that coincides with increase in CO_2 concentration from 280 ppm in 1900 to 390 ppm in 2009) and declinining biodiversity.

To address all the challenges ahead, we should think of an alternate technology such as nanotechnology to precisely detect and deliver the correct quantity of nutrients required by crops in suitable proportion that promote productivity while ensuring environmental safety.

NANOTECHNOLOGY APPLICATIONS IN AGRICULTURAL SCIENCES

Nano-fertilizers for balanced crop nutrition

Fertilizers play a pivotal role in agricultural production. It has been unequivocally demonstrated that fertilizer contributes to the tune of 35-40% of the productivity of any crops. Without the fertilizer input, it is hardly possible to sustain agricultural productivity of our country. Considering its importance, the Government of India is heavily subsiding the cost of fertilizers, particularly urea to encourage farmers to use them to promote productivity of crops. This resulted in imbalanced fertilization and occurrence of nitrate pollution in groundwaters. In the past few decades, use efficiencies of N, P and K fertilizers remained constant as 30–35%, 18–20% and 35–40%, respectively, leaving a major portion of added fertilizers stay in the soil or enter into aquatic system causing eutrophication.

Attempts are being made to synthesize nano-fertilizers in order to regulate the release of nutrients depending on the requirement of crops. A very few nano-fertilizer formulations have been synthesized in China, Germany and USA and are being tested under laboratory conditions. Liu *et al*. (2006) have shown that nano-composites containing organic polymer intercalated in the layers of kaolinite clays can be used as a cementing materials to regulate the release of nutrients from convential fertilizers. This process increases the nutrient-use efficiencies, besides preventing environmental hazard. In another study, a patented nano-composite consists of N, P, K and micronutrients and mannose and amino acids have shown to increase the uptake and utilization of nutrients by grain crops (Jinghua 2004). Both the products have emerged from Chinese Academy of Agricultural Sciences (CAAS), Beijing and they collaborate with Germany for more nano-fertilizer formulations. In India, Bansiwal *et al*. (2006) developed a surface modified zeolite as a carrier of slow release phosphatic fertilizer. Nano-fertilizer technology is very innovative and scanty reported literature is available in the scientific journals. However, some of the reports and patented products strongly suggest that there is a vast scope for the formulation of nano-fertilizers. Fertilizer particles can be coated with nanomembranes that facilitate in slow and steady release of nutrients. This process helps to reduce loss of nutrients while improving fertilizer-use efficiency of crops.

The Tamil Nadu Agricultural University is one of the pioneering institutes initiated research in nano-fertilizers and the preliminary data are quite encouraging. Accordingly, zeolite has been reduced to the dimension of 30-40 nm fortified with nutrients after surface modification using a cationic surfactant hexadecyltrimethyl ammonium (HDTMA) of the negatively charged zeolites. Nano-fertilizers are capable of releasing nutrients, especially NO_3-N more than 50 days while nutrient release from conventional fertilizer (urea) ceased to exist beyond 10-12 days (Subramanian and Rahale 2009). The NO_3-N adsorption on the sheet of zolite has been visualized (Fig 1) under Atomic Force Microscope (AFM). Further, ^{15}N studies were taken using maize as a model system have revealed that N-use efficiency from nano-fertilizer was 82% and the conventional fertilizer (urea) registered 42% with a net higher nitrogen-use efficiency of 40% which is hardly achievable in the conventional system (Fig 2). This suggests that nano-fertilizers may be used as a strategy to regulate the smart release of nutrients that commensurate with crop requirement. Research is underway to develop nano-composite to supply all the required essential nutrients in suitable proportion through smart delivery system.

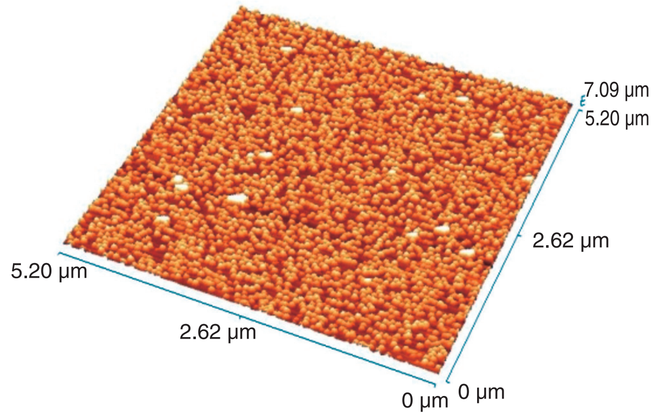

Fig 1 AFM picture showing nitrogen loading in the sheet of zeolite

These literatures suggest that balanced fertilization may be achieved through nanotechnology. The impact of nano-fertilizer products on physiological, biochemical, nutritional and morphological changes in plants and the fate of nano-products in soil and plant systems have to be studied. In addition, the effects of nano-fertilizer products on rhizosphere microorganisms and biogeocycling of nutrients have to be explored under natural field conditions.

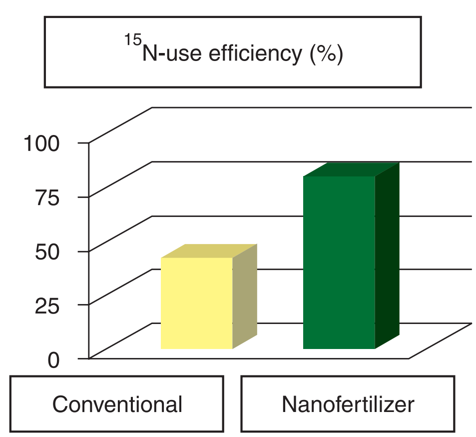

Fig 2 Nitrogen-use efficiency (%) of conventional and nano-fertilizers

Effective weed control

Weeds are unwanted plants in agricultural production system causing yield loss to the tune of 30–40% depending on the intensity of infestation. A wide range of herbicides is used to manage the weeds but found less or ineffective in rainfed agriculture as these chemicals may loose their herbicidal value in the absence of moisture. Encapsulation of herbicides is one of the important strategies to regulate the release of herbicide molecules. In Tamil Nadu Agricultural University, our team has successfully encapsulated herbicide in a MnO_2 core shell shielded with bilayer polymers that open up and exuding the active ingredient on receipt of rainfall (Chinnamuthu *et al.* 2010). They suggest that this method would save time and costs associated with tilling and manual picking.

Enhancing seed emergence

Seed is a basic input deciding the fate of productivity of any crop. Conventionally, seeds are analyzed for their germination and distributed to farmers for sowing. Despite the fact that the germination percentage registered in the seed testing laboratory is about 80-90%, it hardly happens in the field due to the inadequacy or non-availability of sufficient moisture under rainfed system. In India, more than 60% of the net area sown is under rainfed system, it is quite appropriate to develop technologies for rainfed agriculture. Seed coating or hardening techniques have been optimized and extensively studied for a wide array of crops and evolved strategies to ensure germination (Vanagamudi *et al.* 2006). This process will make the seed hardened and emerge faster besides withstanding early drought. Though it is a useful strategy but rarely adopted by farmers due to practical difficulties. This necessitates evolving an alternate and innovative method to tackle the issue of poor germination in rainfed system.

Carbon nano-tubes (CNTs) are nanomaterials widely used in biological and material sciences. Single and multi-walled carbon nano-tubes are commercially available to carry out smart delivery of water, nutrients and medicines etc. Since CNT carries extensive surface area, they have the potential to regulate the moisture under constraints of irrigation or drought conditions. Natarajan and Sivasubramanian (2007) have elucidated various nanotechnological approaches that can be employed in seed science. The approaches include nano-polymer for seed hardening, nano-sensors, nano-barcodes, use of nano-magnetic particles for aerial seeding etc. Recently, Khodakovskaya and his team in 2009 at the University of Arkansas, USA, have reported the use of carbon nano-tube for improving the germination of tomato seeds through permeation of moisture. In this elegant experimental system, the substrate impregnated with differential quantities of carbon nano-tubes. The data have vividly shown that there is a direct relationship between the quantities of CNT and rate of germination (Khodakovskaya *et al.*2009). The authors suggest that CNT serves as new pores for water permeation by penetration of seed coat. Further, the CNT can act as a gate to channelize the water from the substrate into the seeds. The situation can be mimicked in rainfed system wherein moisture is constraint can be tide over through the CNTs. This is the maiden attempt in the field of seed technology to promote germination under rainfed system.

Biosensors to detect nutrients and contaminants

Protection of the soil health and the environment requires the rapid, sensitive detection of pollutants and pathogens with molecular precision. Soil fertility evaluation is being carried out for the past 60 years with the same set of protocols which may be obsolete for the current production systems and in the context of precision farming approaches. Accurate sensors are needed for *in situ* detection, as miniaturized portable devices, and as remote sensors, for the real-time monitoring of large areas in the field. Generally speaking, a sensor is a device built to detect a specific biological or chemical compound, usually producing a digital electronic signal upon detection. Sensors are now used for the identification of toxic chemical compounds at ultra low levels (ppm and ppb) in industrial products, chemical substances, water, air and soil samples, or in biological systems.

Research in the field of nanosensors includes various areas like synthesizing new nanomaterials with specific detection sites able to recognize a certain pollutant; developing new detection methods, to increase the limit of detection of sensors while ensuring a 'readable' electrical signal; and miniaturizing the size of the sensor elements while integrating these with larger parts of the device. An example of how nanoscience can be applied to the sensing technology is shown in Fig 3, which schematizes the operational principle of a heavy-metal nanosensor developed for monitoring heavy metals in drinking water (Forzani *et al.* 2005). The sensor is made of an array of electrode pairs fabricated on a silicon chip and separated by few nanometres. When the electrodes are exposed to a solution of water containing metal ions, these deposit inside the nano-gap in between the electrodes. Once the deposited metal bridges the gap a 'jump' in conductance between the electrodes is registered. The size of the gap, being only few nanometres, allows the detection of a very low concentration of metal ions. This type of sensor is called 'nanocontact sensor' (Fig 3)

Soil solution can be allowed to react with nanosensors that will give accurate measurement of availability of nutrients in the soils. Nanosensors is believed to be used to determine nutrient, moisture and physiological status of plants which assists in taking up appropriate and timely corrective measures. Nanoparticles are mini laboratories that have the potential to precisely monitor temporal and seasonal changes in the soil-plant system. Nanosensors detect the availability of nutrients and water precisely which is very much essential to achieve the mission of precision agriculture.

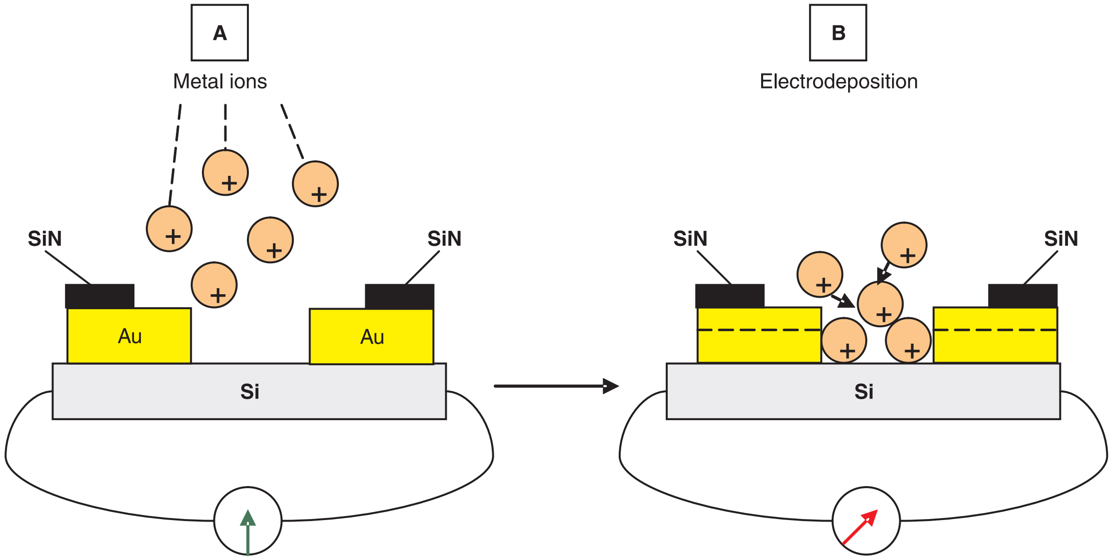

Fig 3 Schematic representation of a nanocontact sensor. (*A*) A drop of a sample solution containing metal ions is placed onto a pair of nanoelectrodes separated with an atomic scale gap on a silicon chip, and (*B*) holding the nanoelectrodes at a negative potential, electrochemical deposition of a single or a few metal atoms into the gap can form a nanocontact between the two nanoelectrodes and result in a quantum jump in the conductance

Smart delivery system

Nano scale devices are envisioned that would have the capability to detect and treat diseases, nutrient deficiencies or any other maladies in crops long before symptoms were visually exhibited. 'Smart delivery systems' for agriculture can possess timely controlled, spatially targeted, self-regulated, remotely regulated, pre-programmed, or multi-functional characteristics to avoid biological barriers to successful targeting. Smart delivery systems can monitor the effects of delivery of nutrients or bioactive molecules or any pesticide molecules. This is widely used in health sciences wherein nanoparticles are exploited to deliver required quantities of medicine to the place of need in human system. In the smart delivery system, a small sealed package carries the drug which opens up only when the desirable location or infection site of the human or animal system is reached. This would allow judicious use of antibiotics than otherwise would be possible. A molecular-coded 'address label' on the outside of the package could allow the package to be delivered to the correct site in the body (Heller and Atkinson 2007). Similarly, implanting nano-particles in the plants could determine the nutrient status in plants and take up suitable remedial measures well before the malady causes yield reduction in crops. The fertilizer or irrigation requirement of crops can be scouted by nanotechnology. The exciting possibility of combining agricultural science and nano scale technology into sensors holds the potential of increased sensitivity and therefore a significantly reduced response-time to sense field problems. Smart delivery systems could contain on-board chemical detection and decision making capability for self-regulation that could deliver active chemical molecules or nutrients as needed. Remote activation and monitoring of intelligent delivery systems can assist agricultural growers of the future to minimize antibiotic and pesticide use.

Nano-devices for identity preservation and tracking

One of the major constraints in Indian agriculture is the quality maintenance of agricultural produce. Proper monitoring of production system through nanotechnology will be very appropriate to promote quality and make clear distinction with organic products. Identity preservation (IP) is a system that creates increased value by providing customers with information about practices and activities used to produce a particular crop or other agricultural products. Certifying inspectors can take advantage of IP as a more way of recording, verifying, and certifying agricultural practices. Through IP, it is possible to provide stakeholders and consumers with access to information, records and supplier protocols. Quality assurance of agricultural products safety and security could be significantly improved through IP at the nano-scale. Nano-scale IP holds a possibility of the continuous tracking and recording of the history which a particular agricultural product experiences. The nano-scale monitors linked to recording and tracking devices to improve identity preservation of food and agricultural products. The IP system is highly useful to discriminate organic versus conventional agricultural products.

Nanobiotechnology

Nanobiotechnology has the potential to increase the efficiency and quality of agricultural production and food storage, to enhance the safety of food supplies for the protection of consumers and producers and to introduce new functionality (value-added products) for food, fibre and agricultural commodities. Nanobiotechnology will pave ways for new researchable areas and applications.

- *New ways to study molecules, DNA and cells for food, nutraceutical and pharmaceutical applications*
  - Provides higher resolution materials and devices for the separation of enzymes and other biomolecules that are key catalysts for industrial biotechnology
  - Offers novel methods for observing single molecule events that can allow assessment of protein engineering efforts focused on important polysaccharide degrading enzymes
- *Advanced instruments and research methods for DNA and protein identification and manipulation*
  - Helps to develop novel laboratory on a chip proteomics technology for assessment of metabolic pathways in important biocontrol agent
  - Assists in rapid and reliable DNA methods for detection of phytotoxins and pathogens in digested and composted animal wastes to determine their subsequent safe use in agriculture
- *Novel nucleic acid engineering based films with more sophisticated and controllable nano and microstructures for agricultural and food applications*

Biological tests measuring the presence or activity of selected substances become quicker, more sensitive and more flexible when nano particles are put to work as tags or labels. Magnetic nanoparticles, bound to suitable antibody, are used to label specific molecules, structures or microorganisms. For example, gold nano particles tagged with short segments of DNA can be used for detection of genetic sequence in a sample. Multicolor optical coding for biological assays has been achieved by embedding different sized quantum dots into polymeric microbeads. Nano-pore technology for analysis of nucleic acids converts strings of nucleotides directly into electronic signatures.

Nano food industry

During last three years, food industries have witnessed that the nanotechnology has been really integrated in a number of food and food packaging products. There are now over 300 nanofood products available on the market worldwide. These exciting achievements have encouraged a large increase of R&D investments in nanofood. Today, the nanotechnology is no longer an empty buzzword, but an indispensable reality in the food industry. Any food company who wants to keep its leadership in food industries must begin to work with nanotechnology right now. The impact of nanotechnology is huge, ranging from basic food to food processing, from nutrition delivery to intelligent packaging. It is estimated that the nanotechnology and nano-bio-info convergence will influence over 40% of the food industries up to 2015. The risk for the food companies lies in not entering the nanotechnology, but entering too late.

The nanofood market has been soaring from US$ 2.6 billion in 2003 to 5.3 billion in 2005 and is expected to reach 20.4 billion in 2010. Nano-featured food packaging market will grow from US$ 1.1 billion. 2005 to 3.7 up to 2010. More than 400 companies around the world are today active in research and development and production. USA is the leader, followed by Japan and China. By 2010 Asia, with more than 50% of the world population, will become the biggest market for the Nanofood, with China in the leading position.

Nanotechnology for environmental safety

A strong influence of nano-chemistry on waste water treatment, air purification and energy storage devices is expected. The scientists of Banaras Hindu University have devised a simple method to produce carbon nano-tube filters that efficiently remove micro to nano-scale contaminants from water and heavy hydrocarbons from petroleum. The filters are carbon cylinders several centimeters long and 1-2 cm wide with walls just one-third to one-half of a mm thick. They are produced by spraying benzene into a tube shaped quartz mold and heating the mold to 900°C. The nano-tube makes the filters strong, reusable, and heat resistant and they can be cleansed easily for reuse. They can remove 25 nano meter sized polio viruses from waster as well as larger pathogens such as *Escherichia coli* and *Staphylococcus aurous* bacteria. If it is used widely, we shall minimize the water-borne diseases. Magnetic nanoparticles offer an effective and reliable method to remove heavy metal contaminations from waste water by making use of magnetic separation technique. Nanotechnology can introduce new methods for the treatments and purification of water from pollutants, as well as new techniques for wastewater management and water desalinization. In TNAU, efforts are being undertaken to use Fe^{o} valence particle to decontaminate soil and aquatic systems (Udayasoorian *et al*. 2009).

Precision farming

Precision farming has been a long-desired goal to maximize output (i e crop yields) while minimizing input (i e fertilizers, pesticides, herbicides etc.) through monitoring environmental variables and applying targeted action. Precision farming makes use of computers, global satellite positioning systems, and remote sensing devices to measure highly localized environmental conditions thus determining whether crops are growing at maximum efficiency or precisely identifying the nature and location of problems. By using centralized data to determine soil conditions and plant development, seeding, fertilizer, chemical and water use can be fine-tuned to lower production costs and potentially increase production – all benefiting the farmers. Precision farming can also help to reduce agricultural waste and thus keep environmental pollution to a minimum. Although not fully implemented yet, tiny sensors and monitoring systems enabled by nanotechnology will have a large impact on future precision farming methodologies.

One of the major roles for nanotechnology-enabled devices will be the increased use of autonomous sensors linked into a GPS system for real-time monitoring. These nanosensors could be distributed throughout the field where they can monitor soil conditions and crop growth. Nanosensors utilizing carbon nano-tubes or nano-cantilevers are small enough to trap and measure individual proteins or even small molecules. Nanoparticles or nanosurfaces can be engineered to trigger an electrical or chemical signal in the presence of a contaminant such as bacteria. Other nanosensors work by triggering an enzymatic reaction or by using nanoengineered branching molecules called dendrimers as probes to bind to target chemicals and proteins. Ultimately, precision farming, with the help of smart sensors, will allow enhanced productivity in agriculture by providing accurate information, thus helping farmers to make better decisions.

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